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HARVESTING THE CLOUDS

Louis J. Battan was born in 1923 in New York City. After having entered City College of New York, he enlisted in the U. S. Army Air Force in World War II. As an Air Force lieutenant he studied electronics and radar at Harvard and M.I.T. Following the war he continued his studies, receiving a B.S. degree in 1946 from New York University, and an M.S. in 1949 and Ph.D. in 1953 at the University of Chicago. During the period 1947 to 1950 he was employed as a research meteorologist for the U. S. Weather Bureau and from 1950 to 1958 was associated with the University of Chicago as a research associate and staff meteorologist.

In 1958, Dr. Battan joined the faculty of the University of Arizona as a professor of meteorology and associate director of the Institute of Atmospheric Physics. Since then he has continued to do research in various areas of physical meteorology. In 1962 he received the Meisinger Award of the American Meteorological Society for research achievements. He has served that society as a member of its Council in 1959–61, as a member of many committees, and its president in 1966–67. He has acted as a consultant to the National Science Foundation, U. S. Weather Bureau, Air Force, Army, and National Institutes of Health and is a member of the Committee on Atmospheric Sciences of the National Academy of Sciences.

Professor Battan was an associate editor of the *Journal of Atmospheric Sciences* from 1962 to 1966. He has written many articles for scientific and technical publications as well as for a number of encyclopedias. He is the author of a number of books: *Radar Meteorology* (University of Chicago Press, 1959), co-author of *Earth and Space Science* (D. C. Heath, 1966), *The Thunderstorm* (New American Library, 1964). This is his fifth book for the Science Study Series, the previous ones being *The Nature of Violent Storms* (1961), *Radar Observes the Weather* (1962), *Cloud Physics and Cloud Seeding* (1962), and *The Unclean Sky* (1966).

HARVESTING THE CLOUDS

Advances in Weather Modification

Louis J. Battan

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WITHDRAWN

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Figures 1, 3, 6 and 8 by Don Perceny.

WITHDRAWN

THE SCIENCE STUDY SERIES

This book is one of a number that will appear in the series through the collaboration of Doubleday & Company, Inc. and the American Meteorological Society.

The Science Study Series offers to students and to the general public the writing of distinguished authors on the most stirring and fundamental topics of science, from the smallest known particles to the whole universe. Some of the books tell of the role of science in the world of man, his technology and civilization. Others are biographical in nature, telling the fascinating stories of the great discoverers and their discoveries. All the authors have been selected both for expertness in the fields they discuss and for ability to communicate their special knowledge and their own views in an interesting way. The primary purpose of these books is to provide a survey within the grasp of the young student or the layman. Many of the books, it is hoped, will encourage the reader to make his own investigations of natural phenomena.

The Series, which now offers topics in all the sciences and their applications, had its beginning in a project to revise the secondary schools' physics curriculum. At the Massachusetts Institute of Technology during 1956 a group of physicists, high school teachers, journalists, apparatus designers, film producers, and other specialists organized the Physical Science Study Committee, now operating as part of Educational Development Center, Newton,

Massachusetts. They pooled their knowledge and experience toward the design and creation of aids to the learning of physics. Initially their effort was supported by the National Science Foundation, which has continued to aid the program. The Ford Foundation, the Fund for the Advancement of Education, and the Alfred P. Sloan Foundation have also given support. The Committee has created a textbook, an extensive film series, a laboratory guide, especially designed apparatus, and a teachers' source book.

Selected Topics in the Atmospheric Sciences

The American Meteorological Society, with the objectives of disseminating knowledge of meteorology and advancing professional ideals, has sponsored a number of educational programs designed to stimulate interest in the atmospheric sciences. One such program, supported by the National Science Foundation, involves the development of a series of monographs for secondary school students and laymen, and since the intended audiences and the standards of excellence were similar, arrangements were made to include their volumes on meteorology in the Science Study Series.

This series within a series is guided by a Board of Editors consisting of James M. Austin, Massachusetts Institute of Technology; Richard A. Craig, Florida State University; James G. Edinger, University of California, Los Angeles; and Verne N. Rockcastle, Cornell University. The society solicits manuscripts on various topics in the atmospheric sciences by distinguished scientists and educators.

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INTRODUCTION

The advance of science over the last few decades has been truly spectacular. Physicists have probed deeply into the atom and are making rapid strides in the utilization of nuclear energy. Though certain diseases still remain to be conquered, medical scientists have had great success in extending human life and are on the threshold of learning the secrets of transplanting human organs. Airplanes are moving almost three times the speed of sound. Computers are so fast that in a second, hundreds of millions of calculations are made. The catalogue of scientific progress goes on and on. The results are being felt in virtually everything we do.

Science is moving forward on a very broad front. But certain scientific frontiers are in need of much greater investigation and exploitation. This book deals with one of them, weather and climate modification.

The consequences of weather control have been considered by farmers, soldiers, statesmen and many others. To some, the possibility that it might be possible to alter the path of a hurricane, for example, is appealing; to others it is appalling. More rain on a dry cornfield would be welcomed, but enough rain to cause floods could be disastrous. If the weather switch were in the hands of a friend, how fortunate you would be. If an enemy could control the weather, he would have a powerful weapon indeed.

Effective large-scale weather modification is still a long way off, but we have learned how to exert some influences on clouds and precipitation. The successes to date encourage us to believe that we can and should learn how to exert greater control on the weather and climate. This can only come about if we are prepared to make greater investments in terms of scientific talent and resources. In view of the crucial nature of this problem, it is essential that the required investments be made.

HARVESTING THE CLOUDS

1

WHY CHANGE THE WEATHER?

Think for a moment about the air around you. What does it mean to life, to health, to comfort, to joy, to sadness?

Over the centuries most people have accepted the atmosphere as they found it. Many have shared the pleasures of deep blue skies, pure white clouds and colorful sunsets. Many have complained of too much or too little rain, too hot or too cold, lightning, thunder, hail, tornadoes, hurricanes and so on. Many have prayed the weather would change, many merely have cursed it. But only a few have believed it could be changed. In this book we will deal with the accomplishments, speculations and hopes of those who have worked to influence and control the weather.

WEATHER AND CLIMATE AND YOU

You could write a book on how weather and climate affect human existence. For the most part, the ways are obvious, but sometimes they are subtle. Some weather events cause almost instant reactions. A hailstorm, for example, can wipe out a field of wheat in a matter of minutes. In other instances, the atmosphere exerts its influence over a long period of time. Several decades of gradual warming can lead to the melting of sea ice over thousands of miles and allow ships to move to northerly parts throughout the year rather than just in the summer months.

When talking about the atmosphere and man, it is convenient to discriminate between short-period effects and long-period ones. Meteorologists have done this for a long time and have adopted the words *weather* and *climate* to distinguish between them.

The term *weather* is used to designate the state of the

atmosphere at any instant of time or over a short period of time. We say, "The weather today is hot and humid in New York" or, ". . . in the eastern United States." It would also be proper to say, "The weather over Europe was cold and wet all winter long." On the other hand, when we speak of *climate,* we refer to average conditions over a great many years. For example, the climate of Yuma, Arizona, is hot and dry. On the average it has a yearly rainfall of only 3.4 inches and its average annual temperature is 72° F. It should be recognized, however, that these figures are averages. Any particular day might be cool and very wet. For instance, in August 1909, 6.2 inches of rain fell in Yuma.

Often the effects of weather and climate on all aspects of human behavior are not fully appreciated. It would be appropriate to examine some of them briefly.

VIOLENT STORMS

Consider first the effects of storms. Almost everyone has had some experience with violent weather in one form or another. The degree of exposure depends to a large extent on where you live. If home is along the shores of the South Atlantic or Gulf of Mexico, the great threat is the hurricane, as it is in certain other parts of the world, notably Japan.

The hurricane is a whirling mass of air covering an area several hundred miles across. As it moves across warm ocean waters, the wind speeds may increase to over a hundred miles per hour. The strong winds set up giant waves and force water towards the coastlines. As a result, the ocean water can rise enough to sweep over low-lying coastal land, destroying property and drowning all living creatures in its path. Torrential rains contribute to the flooding. The strong winds can uproot trees and damage buildings in their path. Tornadoes produced by the hurricane contribute to the death and destruction.

Fortunately, the number of hurricanes striking the United States is small, usually between one and three per year, but sometimes as many as six may occur. There

have been some particularly catastrophic ones. In 1928, one storm moving over the islands of the Caribbean and then over Florida left 2,336 dead. In June 1957, a hurricane from the Gulf of Mexico pushed into Louisiana and parts of Texas. It killed some five hundred people and fifty thousand cattle, mostly by drowning. In September 1967, Hurricane Beulah moved up the valley of the Rio Grande River. It produced fantastic quantities of rain, in some places more than thirty inches in three days. Vast areas were flooded to the rooftops. (See Plate 1.) Fortunately, most people were evacuated and there were relatively few casualties. But the flooding and high winds caused more than a billion dollars worth of damage.

Hurricane damage to property in the United States alone over the last thirty years has *averaged* about $50,000,000 per year, with much greater amounts during some years.

Hurricanes clearly are dangerous, but tornadoes are still more so. Tornadoes sometimes are found in hurricanes, but most of them occur in association with thunderstorms over fairly flat terrain. People who have survived when a tornado passed overhead tell of moments of terror. One instant the air is fairly still; in the next, winds of unbelievable strength tear buildings apart, pick up automobiles and rip down trees and power lines.

Unlike the massive hurricane lasting many days, a tornado is small and short-lived, but it packs a fantastic punch. A typical tornado funnel is less than a quarter of a mile in diameter and touches the ground only for a matter of minutes. Commonly it extends down from the base of a large thunderstorm. As the thunderstorm moves, it may produce many funnels. One dips down and tears up the countryside, then disappears; another protrudes down and continues the devastation.

Tornadoes have been observed in every one of the continental United States, but are more numerous over the Great Plains and Middle West. The states of Texas, Oklahoma, Missouri and Kansas are fertile breeding grounds.

It is easy to explain how *twisters,* as they are sometimes

called, are so dangerous. They are composed of a tight column of air spinning at speeds which may exceed 200 mph. At the center of the column, the atmospheric pressure at the ground is far below normal. As the funnel passes over a building, the pressure on the outside of the walls can suddenly fall by as much as three pounds per square inch. Since the pressure inside the structure usually cannot fall fast enough, a tremendous force is suddenly exerted on the walls and roof of the building. In some circumstances, this sequence of events can happen so fast that the building literally explodes. As the fragments are blown apart, the strong winds pick them up and toss them around like shrapnel. (See Plate 2.)

A violent tornado passing through a city or town deals out devastation on the scale of a bombing attack. Neither the people nor their possessions are spared. There is only one sure protection—that is to get out of the way. In areas with high storm frequencies, many people have storm cellars. If none is available, a basement or an interior hallway affords some protection. If time allows, escape by car or truck is feasible. But usually the decision for action has to be made quickly. One minute the cloud is only a thunderstorm, the next it's a black, roaring mass of destruction.

Is it any wonder that tornadoes are so lethal? The number of fatalities resulting from tornadoes averages more than two hundred per year in the United States. Sometimes that many and more are struck down almost with one blow. During Palm Sunday of 1965, a line of thunderstorms started forming over eastern Iowa. Detailed studies of the storms have been made by Tetsuya Fujita and his associates at the University of Chicago. As the line moved towards the east at about forty knots, the number of thunderstorms became greater. During an eleven-hour period, this squall line set off more than thirty tornado funnels. Some occurred in Iowa, Wisconsin, Illinois and Michigan, but northern Indiana was the worst hit in terms of casualties. The Palm Sunday tornadoes left some 260 dead and perhaps ten times more injured. The property damage was enormous. Over the years, tornado damage

has averaged almost $14,000,000 a year, but in some years has been two or three times as great.

Hurricanes and tornadoes are the firing squads of the atmosphere. There are other storms which do great damage, mostly measured in economic terms. Hailstorms are in this category. During the period 1960 to 1964, hail did an annual average of over $50,000,000 worth of damage to crops in the United States alone. (See Plate 3.) In other parts of the world extensive hail damage also is common—in northern Italy, Switzerland, southwestern U.S.S.R., East Africa, Argentina and many other countries.

Every year, thousands of acres of wheat in the Great Plains of the United States are beaten into the ground by hailstones, sometimes as large as an inch in diameter, on rare occasions the size of oranges. Fruit orchards are very susceptible to hail damage. The vineyards of Italy, Switzerland, France and the Soviet Union frequently are decimated by hail. In Kenya the tender leaves of tea plants are annually destroyed by hail.

Like tornadoes, hail is associated with thunderstorms, those towering masses of clouds producing lightning and thunder. They can be destructive even when they generate neither death-dealing funnels nor the bombardment of ice pellets. Strong winds blowing ahead of a storm at speeds of sixty to seventy knots may flatten a cornfield or strip a tree of leaves as well as fruit. The winds may peel the roof off a house or shatter the plate-glass window of the home next-door.

Thunderstorms usually serve the very vital purpose of bringing rain during the growing season. In the arid regions of the world, the southwestern United States, for example, they are the main source of new water in the summer. But sometimes thunderstorms bring too much rain and the result is floods.

During the spring, the creeks and rivers of southern Arizona are dry. Horsemen use them for riding because they are free of cactus and other plants. But when the rains begin in July these dry stream channels change dramatically. Rain from thunderstorms in the valley and over the nearby mountains drains rapidly into the chan-

nels. On some days they become rushing, tumbling torrents in a matter of hours. Most of the time the quantities of water are not so large that they cannot be retained within the walls of the channel. Sometimes, though, the water overflows the banks and floods nearby towns and cities. The consequences have been reported time and again in the newspapers. Property damage may run into the millions and many times lives are lost.

Thunderstorms have still another attribute that causes distress to man and beast—lightning. Thunder does little damage beyond waking up the baby in the middle of the night, but lightning does much more than mischief. According to official records of the U. S. Forest Service, during the ten-year period ending in 1963, lightning ignited about 1,200,000 fires, which burned nearly 6,000,000 acres of forest. A lightning stroke lasting a hundredth of a second serves as the match to ignite some dry leaves or brush. In a matter of a few days a magnificent creation of nature can be transformed into a scorched landscape of blackened tree carcasses. Possibly a hundred years growth can be wiped out in what amounts to a blink of the eye when measured by the growth rate of a towering pine.

Forest fires are expensive in terms of board feet of lumber, obviously. But equally serious are the losses in terms of beauty and the hardships imposed on the wildlife living in the ever dwindling wilderness areas.

DROUGHT

Why is the United States the greatest food producer the world has ever known? There are several reasons, obviously. Large sums of money and effort have been invested in the development of better types of corn, wheat, rye and other crops, creating species with high yields and strong resistance to disease. Improved fertilizers are used in large quantities. More efficient machines for working the soil and for cutting and harvesting products are continually developed.

There is still another reason for our high productivity.

With a few exceptions, the weather has been favorable for farming over the last two decades. Certainly there have been parts of the country where during any one- or several-year period it has been too dry or too wet. For the most part, however, the weather had been good for growing. It has had to be, because our grain production in particular has come from dry-land farming, depending directly on rainfall.

The young readers surely do not remember the 1930s. This was the time of the great dust bowl era, when for three years a massive drought plagued the central part of the United States. (See Plate 4.) The soil was dry; the plants died and loosened the anchors holding the ground together. Strong winds scoured the earth, layer by layer. Huge clouds of pulverized topsoil were transported over thousands of miles.

The term *drought* is defined in the dictionary as "prolonged dry weather." When you read this, you may wonder, "How prolonged?" and "How dry?" It just is not possible to give an all-inclusive answer, because it depends on how rain water is used. If corn dies in the field for lack of water, you can say a drought occurred. If cattle on an open range suffer because of empty water holes, the same can be said. When the city of New York has to reduce lawn-sprinkling and the operation of air conditioners, it again is legitimate to state that a drought has hit the area.

When living organisms are suffering because of a deficiency of rainfall, a drought is occurring. Thus the criterion for the presence of drought is more biological than meteorological, even though weather factors bring it about. In some regions, such as the northeastern United States, twenty inches of rain in a year represents drought conditions. On the other hand, the same quantity of rainfall in southern Arizona would represent a year of water abundance. The damage suffered by plants during a drought depends not only on the rainfall but also on the species of the plant and the properties of the soil. Therefore, even in a single region, a prolonged dry spell may harm some plant communities and not others.

Although drought is determined more by biological than meteorological criteria, meteorologists have sought to derive a definition based on rainfall. No definition has been entirely satisfactory, because of the complicated and variable relationship of weather, plants and animals. But obviously the smaller the actual rainfall when compared with the average rainfall, the greater the likelihood of a drought and its serious consequences.

Every year, some parts of the United States suffer drought conditions, with the loss of agricultural products. It has been estimated that the losses of wheat and corn alone exceed 100 and 500 million bushels per year. During the severe and widespread droughts from 1934 to 1937 and from 1952 to 1956, the losses were much more serious than the average annual amounts.

The prolonged dry spell in the northeastern United States during the early and middle 1960s made that part of the country more conscious than ever before of the importance of rain and snow. But in many parts of the world, clean, fresh water has always been thought of as being inexhaustible and virtually free. And it has been almost that. It is said that if you could package a thousand gallons of water to send through the mails, the cost of the water would be about the same as one airmail stamp—about ten cents.

For this reason, there have been few restrictions on water for personal use. A shower a day has been regarded as an inalienable right. Watering the lawn, washing the car, filling the swimming pool, not fixing the leaky faucet also have been every man's privilege. As long as the number of uses and users has been relatively small and the atmosphere has fed the reservoirs in normal amounts, the supply of water has represented few problems in the eastern states.

When nature cuts the water supply in half and consumption goes on at a luxurious rate, enormous problems arise. Reservoirs dry up, river flows diminish. The quantity of fresh water going from the river mouth into the ocean decreases and salt water begins to advance, first toward the river, then up its channel. At times this can go on until the

intake pipes for fresh water begin drawing brine. This almost happened to Philadelphia in the summer of 1965 as ocean water began moving up the Delaware River.

By the summer of 1967, the rainfall in the eastern United States had increased and the New York City reservoirs were near capacity, up from a figure of 40 per cent in 1965. But no one should assume that the crisis is over for once and for all. Perhaps for once, but not for all. Variability is the nature of weather. Whether you look at daily, monthly, yearly or even century rainfalls, there are wet periods and dry periods.

When we think of the effects of droughts, we picture dried-out corn plants, or brittle wheat fields stunted and parched. But dust storms are also a not infrequent accompaniment.

The month of March 1936 saw the creation of dust storms of mammoth proportions over the southern Great Plains. Rain and snow during the preceding year and a half had been less than 60 per cent of normal. The ground was dry, the crops were dead. As is often the case, inadequate rain was accompanied by temperatures several degrees above the long-term average, another factor contributing to the desiccated state of the soil. There was little to hold the earth together. The natural vegetation had been cleared to plant grain, but the grain had died.

The Plains, with no mountains, few trees and little else to break the wind, represented a fairly smooth surface over which the air ran fast and free. During March of 1936, dry weather systems swept the Plains with strong winds and little rain. These winds picked up the soil and carried it in great quantities high into the sky. In some places the air was so full of dust that even during the daytime, visibility was sometimes less than a hundred yards.

During the great drought, dust over the Great Plains was carried to altitudes of over twenty thousand feet and transported far to the east. There were reports of *red rain* because of the large quantities of red soil particles washed down from the sky by raindrops. The rain caused some excitement, but except for coating exposed surfaces with a layer of red dust, it did little harm.

The losses caused by drought and dust storms during the thirties were enormous; as topsoil was blown away and farm buildings were buried in dunes, farmers and businessmen went bankrupt. There was great misery for millions of people, landowners and field hands alike. In those days land management practices were almost nonexistent. Today modern methods can do much to alleviate the consequences of another drought. But the success of dry-land farming hinges crucially on the atmosphere. If the rain and snow do not come, crop failure certainly will result.

DELUGE

At the other end of the hydrological spectrum from drought is the flood. Thunderstorms may cause damage by filling stream channels and causing flash floods, but more disastrous flooding comes about in other ways. Flash floods usually are fairly local in nature, affecting a relatively small area and few people. When major deluges occur over the drainage basins of the large river systems, water overrunning the banks can spread over vast areas. The Ohio, Missouri and Mississippi rivers flood almost regularly.

A general sequence of events leading to major floods in the United States has been repeated time and again. During a cold, wet winter, a blanket of snow is deposited over the Middle West. If temperatures are sufficiently cold, the ground freezes and snow can accumulate with relatively little melting. If in the spring, a warm, humid mass of air moves northward and heavy, warm rains are produced, flooding is likely. The rain added to the melting snow leads to large quantities of water rushing towards lower elevations. With the ground frozen, little water is absorbed by the soil. Since tributaries and main channels are not large enough to handle an excessive quantity of water, it overflows their banks.

Floods have been natural events for a mighty long time. During periods of excessive rain, particularly when combined with melting snow, rivers have spread over the

plains bordering their edges. When land was plentiful and people were few, they lived on higher ground and were not seriously affected by high water in flood stage. But as the population increased, people began building homes and businesses closer and closer to stream channels. In doing this, they destroyed natural vegetation cover which had drunk up water and held back rain runoff. Eventually they paved large areas with asphalt and concrete, further reducing the amount of absorbing soil and increasing the runoff.

These activities of man have increased the possibility of floods and caused them to be more disastrous when they do occur. Fortunately, in many places counteraction can and has been taken in recent times. Dams and reservoirs have been constructed to control flood waters. These corrective measures have not eliminated the problems by any means, but they have certainly helped.

A memorable flood occurred in January and February of 1937, when the Ohio River flooded and caused devastation all along its path, especially in Louisville, Kentucky. The tally sheet showed 436 people dead and more than half a billion dollars in damage. In 1965, heavy rain for several days over eastern Colorado produced tremendous flooding over the banks of the Platte and Arkansas rivers. Damage was well over 200 million dollars.

Earlier we mentioned that hurricanes push ocean water over low-lying land, causing great destruction and loss of life. Usually, the rain of a hurricane is not alone sufficiently intense and long-lived to cause major floods. Occasionally, however, it does just that. In August 1955, two hurricanes within a week passed over Pennsylvania, New York and New England. The rainfall caused monumental flooding with total damage of about one billion dollars.

Not much more need be said to emphasize the point that too much rain in too short a time produces floods costing lives and property. In varying degrees they occur every year.

SNOW

What would you say is one of the most beautiful sights you have ever seen? Try this one: the view on a cold, crystal-clear morning following an unexpected snowfall. In a large city, the blanket of snow brings about a transformation. Everything is white and clean. As you look across the street, the snow folds smoothly over the curbs in graceful curves. The sun, reflecting from random crystal faces, gives the surface a sheen of brilliant purity.

Of course, in a city it does not last long. By the time the sun reaches only a few degrees in the sky, alarm clocks ring, signaling the start of another day. Within the hour the rush begins for office and factory. The snow is shoveled and pushed, stamped and run over. Tempers flare as cars get stuck or slide. Invariably there are big skids and dented fenders. In very short order the movement of men and machines creates dirty piles of ice lining the streets, impeding pedestrians and vehicles alike. (See Plate 5.)

If you live in a city, you pay for a few short moments of natural beauty with days or sometimes weeks of inconvenience. Snow can be a big nuisance, a very costly one, too, if the weather stays cold and the snow has to be cleared away with sweepers and trucks. How much better it would be if snow fell only in the country and in the mountains, where its melting could do some good. But even in the wide-open spaces, when snow is excessive, it creates serious problems by making roadways impassable and isolating sheep and cattle on the open range.

AIR POLLUTION

Much has been written on how the air acts as a carrier for a myriad of particles and gases capable of harming humans, animals, plants and even materials as durable as stone and steel. Under certain circumstances the atmosphere acts to spread the poisonous substances from smoke-

stacks, exhaust pipes and other sources through large volumes of air.

Sometimes the atmosphere becomes stagnant over a small area, allowing contaminants to accumulate. If the concentrations of such substances as sulphur dioxide, nitrogen dioxide, carbon monoxide, ozone or hydrocarbons become sufficiently high, serious troubles begin. Eyes smart, lungs become congested and oxygen transfer into the bloodstream diminishes. Weak hearts may not be strong enough to keep going.

The toll of air pollution on human health is hard to measure precisely, because pollution works slowly and often cannot be isolated from other deleterious influences. For the same reason, we cannot accurately estimate the damage to animals, plants and materials. The overall costs of air pollution, however, certainly must run over several billion dollars per year in the United States alone.

UNDERSTAND, PREDICT AND CHANGE

Many more examples could be cited of how weather and man interact: the effects of frosts on crops, particularly berries and citrus fruit; the plant diseases that thrive during prolonged periods of high humidity; the relationship between certain human diseases and the weather; the productivity of domestic animals in different kinds of weather. (To illustrate the last point, we might mention that chickens lay more eggs when they live in air-conditioned comfort than when they reside in a hot barn.)

Many of the relationships between the atmosphere and the biological community are still poorly known. A great deal about atmospheric phenomena is still inadequately understood. It is essential that we learn more about them and about the natural laws that govern them. There is a beauty in understanding that many people still do not appreciate. But almost everyone appreciates prediction. A great many people would be unimpressed or even bored by an explanation of why it rained yesterday, but an accurate prediction of rain tomorrow would get loud applause.

Traditionally, the most important utilitarian function of meteorologists has been weather forecasting. It is a difficult job and sometimes an emotionally trying one as well. The essence of forecasting practice is to observe what is happening now and use that information as a basis for the prediction of future events. Unfortunately, the existing state of the atmosphere cannot satisfactorily be observed by means of techniques in use today. Furthermore, knowledge of the physical laws required for accurate forecasting of atmospheric changes is inadequate. Much more research is needed on a number of links in the forecasting chain.

Weather forecasters realize the limitations in available procedures and practices, but they cannot wait until better ones are developed. To meet deadlines, they must use whatever techniques are presently at hand. Sometimes they issue forecasts with confidence; at other times they recognize that the forecast may go sour. Of course, if the prediction is simply for *rain* or *no rain,* the public has no way of knowing the forecaster's confidence in his own product. Nowadays there is a growing trend to express forecasts in terms of probability—the higher the probability of rain, the greater is the confidence of the forecaster that it will, in fact, rain.

Although weather forecasting can stand substantial improvement, most of the time the predictions are right, or at least accurate enough to be useful. Having an informed judgment of what the weather will be, it is possible to plan courses of action. When a hurricane is coming, inhabitants can evacuate the threatened area in advance. When a freeze is coming, farmers can start the smudge pots to protect the orange groves or cranberries. If rain is predicted, you can carry an umbrella. There are countless examples of how the weather forecast is used to guide everyday activities.

But should man be satisfied merely to understand and predict the weather? Of course not! Why should he sit back when a weather calamity is about to descend on him if there is even the slightest chance that he can do something to prevent it?

Although interest in influencing the weather dates back through the centuries, only in the last few decades has there been progress in developing promising techniques for weather modification. In earlier years there was insufficient knowledge about clouds and rain and the structure of storm systems. As scientists learned more about these and related phenomena, it became possible to formulate reasonable procedures for changing clouds and precipitation.

In the last twenty years or so it has been conclusively demonstrated that some cloud systems can be modified. There has been considerable research aimed at developing schemes for influencing rain, snow, hail, lightning, thunderstorms, hurricanes, cyclones and even the weather over the entire country. In the chapters that follow, we shall examine the work of the past and that going on today, and gaze into the crystal ball for tomorrow.

2

RAIN DANCING AND CANNONS ROARING

Many strange, wonderful and useless ceremonies have been employed to change the weather, particularly to bring more rain. Primitive peoples in every corner of the earth have developed practices based on religious beliefs or the traditions of the tribe.

In the western United States certain Indian tribes such as the Hopi in Arizona still make use of the rain dance. While drums beat and moccasins shuffle and stamp the dust, the spirits of the heavens are implored to shed water on the parched ground. Sooner or later it rains. If sooner, the tribe rejoices; if later, the chief seeks out reasons why the gods are displeased.

A truly outstanding collection of aboriginal and ritualistic practices for increasing rainfall was assembled in 1890 by Sir James G. Frazer.* Many of the rituals involved a human imitation of nature; for example, rain was encouraged by sprinkling water. The following quotations are good illustrations:

> In the Wotjobaluk tribe of Victoria the rainmaker dipped a bunch of his own hair in water, sucked out the water and squirted it westward, or he twirled the ball around his head, making a spray like rain.
>
> In Roumania . . . scantily attired girls go in procession from house to house singing for rain and are drenched by the people with buckets of water.
>
> In Kursk . . . when rain is much wanted, the women seize a passing stranger and throw him into the river or souse him from head to foot.

Certain objects have been thought to have magical rain-

* *The Golden Bough* (New York: Criterion Books, Inc., 1959).

making powers. Stones, in particular, have been regarded with particular favor. According to Frazer:

> The Turks of Armenia make rain by throwing pebbles into the water. At Egin the pebbles are hung in two bags in the Euphrates; there should be seventy thousand and one of them.

These and many other ancient rites were based on superstitious beliefs. In a sense, they did some good. The people who practiced them felt relieved. They probably slept better at night in the belief that all that could be done was done and the rest was in the hands of the gods. Certainly these customs did not produce rain.

BLASTING THE WEATHER

Even before the invention of gunpowder, there were those who believed that loud noises could influence the weather. Some two thousand years ago, Plutarch declared, "It is a matter of current observation that extraordinary rains generally fall after great battles." When the clashing of swords and lances was replaced by the firing of guns and cannons, the sound of battle increased and belief in its association with the weather became fairly common. R. Ward* quotes the memoirs of Benvenuto Cellini as stating that "an impending rain storm was averted in the year 1539, on the occasion of a procession in Rome, by his firing off artillery in the direction of clouds which had already begun to drop their moisture."

Church bells and gunshots to create noises to drive the evil spirits from clouds were used fairly extensively in the middle of the eighteenth century. Most of this activity was intended to prevent the fall of damaging hail. Since the mountainous parts of southern and central Europe have always had destructive hailstorms, interest in this practice was centered there. Farmers in Italy, Switzerland and Austria concerned with protecting fruit orchards and vine-

* R. De. C. Ward, "Artificial Rain," *American Meteorological Journal,* Vol. VIII, May 1891–April 1892, p. 484.

yards from sudden annihilation by hail were ready to make use of any scheme that might work. Many became convinced that bell ringing and cannon firing could ward off hail.

The practice of hailstorm shooting apparently became widespread, for in 1750, Archduchess Maria Theresa of Austria prohibited the use of guns for hail suppression. The reason for her action was that a great many disputes arose among the owners of adjacent land over the effects of the firing. Since the hail often fell somewhere, shot or not, the man on whose land the hail fell blamed his neighbor for not properly controlling his firing. Since liability suits settled in a courtroom were still a thing of the future, violent disputes arose. The empress, realizing the impossibility of deciding liability, put an end to the matter by decree.

Bell ringing during severe thunderstorms was made illegal in the British Empire in the late 1700s. The restriction was instituted because too many bell ringers were being electrocuted by lightning. As you would expect, the ban was difficult to enforce and the electrocutions continued, but at a reduced rate.

It appears that over the next century the guns roared and the bells tolled at a relatively subdued pace. But in 1896, after some twenty years of damaging hailstorms in the Steiermark district of Austria, there was a great resurgence of the hail cannon. Albert Stiger, the mayor of the town of Windisch-Feistritz, designed a special, particularly noisy cannon and set up a network of thirty-six of them to protect the valleys of the district.

The results during the first year of operation were spectacular. No hail damage occurred. The news spread rapidly all over Europe and Stiger's methods were widely copied. But over the next few years results were mixed. In some places there was less hail and in others more hail. The believers were quick to explain the good results in terms of the efficacy of the cannons, the poor results on improper use of the cannons.

By 1902, the Austrian Government still was not convinced of the worth of the hail cannons and was concerned

about the number of casualties. In 1900, for example, eleven people were killed and sixty seriously injured because of accidents in the course of storm bombardments.

An international conference was called to judge the value of the artillery approach to hail suppression. With only a few dissenters, it was concluded that the method could not be ruled out as ineffective, but rather that some carefully controlled tests should be carried out.

Two areas were selected, one in Austria, the other in Italy. Guns and manpower were supplied and the tests began. After two years of operation, the inability of the cannons to prevent the fall of hail was demonstrated by the occurrence of several destructive hailstorms over both areas. According to B. Oddie,* in 1907, Austrian professor J. M. Pertner, summarizing the results of the tests, wrote the following:

> For all scientific purposes and indeed for all objectively thinking agriculturalists, the matter is settled. We are justified by the total failures at Windisch-Feistritz and Castel-Veneto as well as by the failure, demonstrated in Italy, of rockets and bombs, in saying that the end of "weather shooting" has been sealed.

Over the following decades, the use of the hail cannon diminished almost to the point of disappearing, but not quite, and subsequent events have shown that Professor Pertner was far from correct in his final conclusion. During the 1950s another surge of hailstorm shooting began and continues today in varying degrees in various parts of the world. In particular, there has been widespread use of small rockets by farmers in southern Europe and East Africa. It has been reported that following the firings, the falling hail has been softer and less damaging to the plants. Some of these results are difficult to understand, but they will be examined in more detail in a later chapter.

* B. C. V. Oddie, "The Hail Cannon, An Early Attempt at Weather Control," *Weather,* May 1965. An excellent account of the history of the hail cannon.

3

MAN, MACHINES AND THE ATMOSPHERE

When we use the expression "weather modification," we usually are talking about the purposeful changes of cloud and storm systems. In a more general framework it can mean modification of man's environment, either intentionally or inadvertently. In this sense, man has been influencing the atmosphere for a very long time.

INTENTIONAL CHANGES OF CLIMATE

Tens of thousands of years ago man lived as the wild animals do, seeking shelter from the weather in caves. But as intelligence and tools evolved, he began to realize that there were better ways to survive the cold and wind and other natural enemies. He built shelters of wood and stone. At first they merely kept the rain off his head and allowed a fire to warm him. Then he added walls to keep out the wind. The development of houses was a means of modifying the atmosphere for better living.

If we slide quickly over the years and look at a modern building, we see a highly modified environment. Air conditioning maintains nearly constant temperature and relative humidity in summer and winter. Rain, snow, gusty winds and dust have effects only to the extent that they influence the operation of the air-conditioning plant.

Some of the same ideas carried out to keep humans more comfortable and healthy have been found to be beneficial for animals as well. Earlier we mentioned that hens are more productive in a cool environment. Hogs eat more and gain weight faster when they are protected from the scorching heat of an Iowa summer. Cool, contented cows produce more milk. Agriculturalists are now employing various schemes to change the atmosphere in which livestock live, grow, produce and reproduce.

If the farmers of the world depended only on nature to water their fields and keep them adequately warmed, there probably would be fewer farmers and there surely would be more hungry people. This is particularly true in those regions with marginal agricultural climates—the hot, dry deserts and the cold tundra. In order for these areas to be productive, the plant environments have to be modified. This has been done in many ways.

Irrigation is a form of climate modification. It affects the so-called *microclimate,* the climate of the very lowest layers of the atmosphere. The water also cools the soil and vegetation while it is serving as a vehicle for carrying nutrients into the plants.

Low temperatures represent a serious hazard to many plants. Citrus crops, found in warm areas such as Florida, Arizona, California, Spain and Israel, are particularly sensitive. When temperatures fall below the level of zero Celsius, there is danger of frost. The temperature at which specific trees suffer damage depends on the species and age of the plant. Lemons are more susceptible than navel oranges, for example.

It is not unusual for the citrus regions of the United States to be invaded by cold air. On such occasions, it is essential that the atmosphere over the citrus trees be modified. Various practices have been employed to warm the air surrounding the trees. One of them involves the use of a network of oil heaters in the orange grove. (See Plate 6.) As long as the winds are light, the heaters may raise the air and tree temperatures by several degrees and hence prevent or reduce frost damage.

On clear nights, air temperatures often decrease rapidly as heat is radiated outward from the earth. In these situations the temperatures near the ground may be many degrees lower than those at an altitude of two hundred feet. Meteorologists say an *inversion* is present, because the temperature increases with height. Some citrus groves use power-driven propellers to stir up the air, bringing warm air down and mixing cool air upwards. By this means, the trees may be sufficiently warmed to avoid injury by frost.

Many other schemes for changing the microclimate have been used to make agriculture more productive. For example, cranberry fields are sometimes flooded with water to keep the plants warm. An ingenious method has been used for decades in Russia. In the northern provinces, where snow is plentiful, the length of the growing season is short. The sooner the snow melts and the ground defrosts, the longer the season. In order to hasten these events, the snow is dusted with dark soil and carbon black, causing the snow surface to absorb more of the sun's radiation than it would if it were clean. As a result of the additional heat, the snow melts faster and exposes the ground to solar radiation. This makes possible earlier planting than would have been the case if nature had been left undisturbed.

In recent years there has been increasing activity in the study of plant growth in large greenhouses made of plastic. To a certain extent, the concepts adopted by man to keep himself comfortable are being adapted for the cultivation of certain types of vegetation. They are grown in controlled environments. These new ideas may bring about dramatic changes in agricultural practices, especially in some regions of the world most hostile to agriculture. There is mounting evidence that these new techniques will be particularly useful in the desert areas.

UNINTENTIONAL CHANGES IN CLIMATE

In every case we have mentioned of the ways that people have changed the properties of the air in which they live, the changes were made on purpose for a specific reason. Also in every case, the changes were under control and could be reversed. But there are certain types of climatic changes brought about by man over which he has little control.

In a large city, the weather elements are different from those in the surrounding countryside. As buildings are raised one against another and the streets become deep canyons used for funneling cars and trucks, the properties of the air are changed. People and machines produce

large quantities of unwanted gases, smokes and dusts. When the winds are weak, these pollutants collect over the city. (See Figure 1.) Vertical motions of the air may mix them through a depth of several thousand feet.

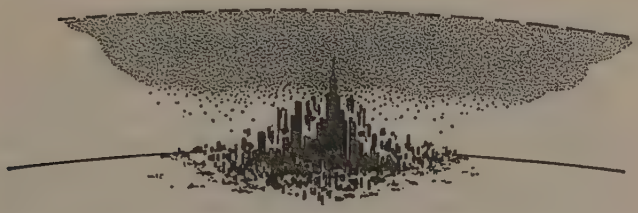

Fig. 1 Smoke and dust accumulate over a large city.

When approaching a large city such as Chicago, you often see a huge "dust dome" over the entire city. This blanket of particles interferes with the transfer of radiation. During the day, some of the sun's rays are absorbed and reflected by the particles and do not reach the ground. This may cause daytime temperatures to be slightly lower than in the open country. At night the particles and gases absorb some of the radiation from the ground and buildings and keep the city warm. As a consequence, the daily range of temperatures in a city is smaller than in the adjacent rural areas. The great masses of stone and bricks in city buildings warmed during the day, cool off slowly after the sun goes down. This fact and the trapping effects of the dust dome lead to hotter summer nights in the cities. Sometimes on summer evenings, city temperatures may be 10 to 15° F higher than those in the country. The smokes in cities also act to make fogs more frequent—not because of higher humidities but because the particles act as nuclei on which water condenses to form droplets.

The worst aspects of city air pollution are the effects on humans, animals, plants and materials of the many toxic substances given off by motor vehicles, smokestacks and other mechanisms of urban life. The problems of a contaminated atmosphere have been discussed else-

where.* They are widely recognized, and, to a certain extent, can be solved by the application of available technology, providing the smoke producers, city planners and taxpayers are prepared to make the necessary investments.

POLLUTION IN THE ATMOSPHERE

Since the turn of the century, immense quantities of fossil fuels—coal, oil and gas—have been burned. Modern civilization has been powered largely by means of these energy sources. The only exceptions have been hydroelectric power and, in more recent times, nuclear power. In years to come the last of these certainly will make ever-increasing contributions, but, for the foreseeable future, the consumption of coal and petroleum products will be on the rise. As these substances are burned they release carbon dioxide (CO_2).

It has been reliably established that since about 1890 the concentration of carbon dioxide in the earth's atmosphere has increased by about 10 per cent, to about 330 parts per million of air. The concentration of CO_2 in the air depends on the amounts taken up by plants, exchanges with the ocean, and several other factors, as well as on the quantity released by combustion. It appears that the observed increases of CO_2 correspond reasonably well with the amount released by fossil fuels consumed over the same period.

According to present estimates, most of the world's reserves of coal and oil may be used up over the next few hundred years. If the past pattern is followed, concentrations of CO_2 in the atmosphere might roughly double during this time and reach a level of perhaps 600 parts per million. What is likely to be the effect of the increases of carbon dioxide?

From about 1890 to 1940, average world-wide temperatures increased almost 1° F. (See Figure 2.) That may not seem too significant. If you were talking about a

* L. J. Battan, *The Unclean Sky* (New York: Doubleday Anchor Science Study Series S46, 1966).

cup of coffee or a bathtub full of water, a 1° F temperature change would be trivial. But when considering the entire world, such a temperature change in the atmosphere represents a tremendous amount of energy.

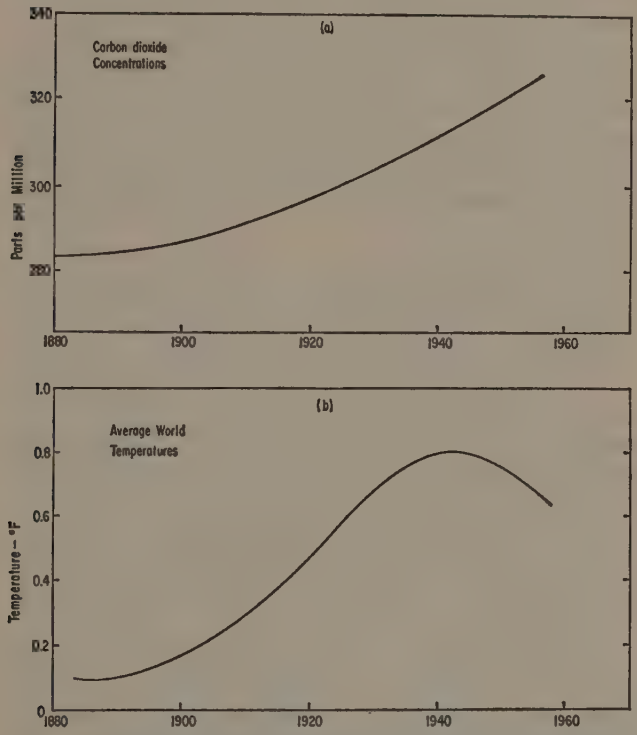

Fig. 2 Smoothed curves showing change of (a) carbon dioxide and (b) temperature from 1880 to 1960. From a report by J. M. Mitchell, Jr.

As a matter of fact, it would take about 7×10^{14} kilowatt-hours* of energy to bring about a 1° F in-

* 7×10^{14} is a scientist's shorthand symbol for 7 with 14 zeros after it. In this system $1000 = 10^3$ and $1{,}000{,}000 = 10^6$. Also, $1/1000 = 10^{-3}$ and $1/1{,}000{,}000 = 10^{-6}$.

crease of the entire atmosphere. That is equivalent to more than 30,000,000 World War II twenty-kiloton atomic bombs. Also, the heat is enough to melt about 8×10^{12} tons of ice. If you had a field of sea ice three meters thick (a reasonable estimate), the amount would correspond to an area of 3×10^6 square kilometers or about one million square miles.

Clearly, a 1° F rise means the atmosphere has absorbed great quantities of heat. It has been proposed that it might have occurred because of the CO_2 released by burning fossil fuels. In order to explain how CO_2 gas might cause warming, it is necessary first to say a few things about the process of radiation.

All things radiate heat, but the character of the radiation depends, to a great extent, on the temperature of the substance. We know that P, the power emitted by a body having a temperature T is given by the expression $P = kT^4$, where k is a constant depending on the properties of the body. This simple equation, known as the Stefan-Boltzmann Law, shows that if the temperature doubles, the radiation increases by the fourth power of 2, that is, by $2 \times 2 \times 2 \times 2$, or by 16. Since the temperature of the sun may be regarded as 6,000° C, while the temperature of the earth averages about 15° C,** the energy radiated by the sun is vastly greater than that from the earth.

The temperature of an object also determines the wavelength of its radiation: the higher the temperature, the shorter the wavelength. The sun's radiation is most intense in the visible spectrum between violet and red. The earth's radiation is composed of much longer waves. They are in the spectral region called the *infrared.*

This name came into being because the region extends beyond the red end of the visible spectrum. Infrared waves cannot be seen with the eye. Nevertheless, they

** Note the temperature in degrees Fahrenheit is given by $F = \frac{9}{5}C + 32$. Hence the average earth temperature is about 59° F.

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transfer considerable energy. Weather satellites carry instruments to measure the outgoing infrared radiation.

The essential point to remember is that radiation coming down to earth from the sun is in the form of short waves, while radiation from the earth is carried by long waves. Carbon dioxide plays an important role in the atmosphere because it can discriminate between the short and long waves. (See Figure 3.) The radiation from the sun passes through the CO_2 gas virtually without absorption. On the other hand, when the long, infrared waves pass upwards from the earth, some of them are absorbed. They warm the air instead of passing to outer space.

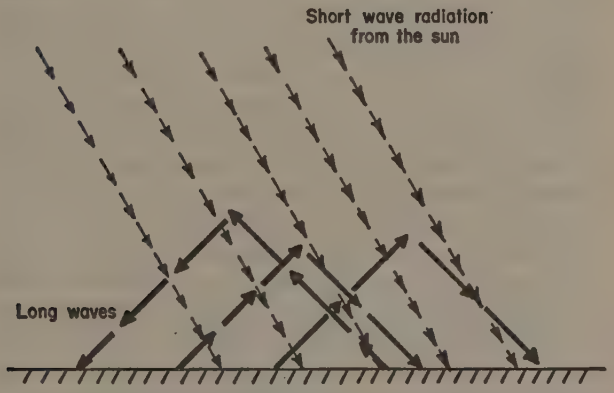

Fig. 3 Schematic illustration of the effects of carbon dioxide gas in the atmosphere. Short-wave radiation from the sun passes through the atmosphere to the ground. Long waves are partly absorbed by the CO_2 gas and re-radiated back to earth.

Various scientists have made calculations of the amount of atmospheric heating which might be produced by CO_2 in the air. Syukuro Manabe at the Environmental Science Services Administration in Washington has made some of the most recent computations. He found that, in theory, the observed 10 per cent increase in CO_2

at the turn of the century could have led to a temperature increase of about 0.4° F at the earth's surface. An increase from 300 to 600 parts per million, which our past pattern of fossil fuel burning indicates could happen in the next few hundred years, could lead to an increase of about 2.5° F.

We noted earlier that from about 1890 to about 1940 the average world-wide temperature rose about 1° F. Some scientists suggested that it may have been caused by the increased CO_2 in the atmosphere. Since that time, however, there has been a general cooling and this has caused many authorities to doubt that global temperatures are crucially controlled by the CO_2 concentration. Some geophysicists have suggested that the general cooling of the earth is being caused by increases in particulate pollutants in the atmosphere. Reid A. Bryson at the University of Wisconsin has produced evidence that the quantities of atmospheric dusts are increasing. He argues that this is causing the cooling observed during the past few decades. Small particles in the atmosphere have small effects on outgoing long wave radiation, but they do act to reflect some of the incoming short waves from the sun. The net result is a cooling at the earth's surface.

Substantial increases in atmospheric particles during the ten-year period ending in 1967 also have been found at the Mauna Loa Observatory in Hawaii. The dust trapped in the glaciers of the Caucasus Mountains increased markedly in quantity after about 1930.

We shall have to wait and see if the atmosphere continues cooling or starts warming up again. If the warming observed earlier in this century was caused by the CO_2, the temperature curve might resume its climb. On the other hand, continued pollution of the earth's atmosphere by smoke and dust may have the opposite effect. In either case the relatively small changes in global temperature can have very important consequences.

Earlier, some rough estimates were made of the amount of sea ice which could be melted if the energy represented by a 1° F increase could be used for this purpose. If heating were to proceed to the point where

all the ice and snow in both the Arctic and Antarctic were to melt, it could lead to a rise of sea level by perhaps thirty meters, according to some crude estimates reported by J. R. Rossiter at the University of Liverpool in England. He also notes that this is ". . . an improbable occurrence in the foreseeable future (unless nature is assisted by man's surplus of hydrogen bombs)." Nevertheless, much smaller rises in water levels can cause great distress to regions at low elevations close to the sea. Rossiter notes that the likelihood of dangerous surges of sea water over the coasts of England could be doubled or tripled if mean sea level were to rise only about 0.5 feet (0.15 meter). At least in a qualitative sense, this conclusion can be extended to cover low-lying coastlines all over the world.

It just is not possible to predict accurately what air temperatures and sea level will do over the next century. The interactions between atmosphere and ocean are complex and, in some regards, very obscure.

Manabe's computations indicated that low-level atmospheric warming caused by high concentrations of CO_2 would be accompanied by cooling in the stratosphere. It seems reasonable to expect that, if this came about, the motion of air and storm systems would be affected. This in turn could have tremendous effects on the climates over the globe. Unfortunately, no one can yet predict what the results will be.

THE LA PORTE WEATHER ANOMALY

La Porte, Indiana, is a small town about thirty miles east of the industrial complex of east Chicago and Gary, Indiana. In 1968, Stanley A. Changnon, Jr., a climatologist at the Illinois State Water Survey, showed that during the period from 1920 to about 1945 there was a pronounced increase in rainfall at La Porte. During the same period, nearby stations, such as South Bend some ten miles away, experienced little precipitation change.

The major increase in La Porte precipitation occurred during the warm season of the year. It was accompanied

by a rise in the number of thunderstorm days reported at La Porte. Changes in snowfall exhibited only small increases between 1920 and 1945.

Changnon also assembled observations of the number of days with smoke and haze at Chicago. During the period 1935 to 1945, there was a marked increase in the frequency of such days. At first glance it would be tempting to ascribe the changes of La Porte precipitation to the addition of cloud-forming particles emitted from the smokestacks of the upwind industries. Because of the fact that the major discrepancies in La Porte's weather occurred as a result of summer clouds, Changnon rejected this explanation. Instead, he speculated that the rainfall increases occurred because heat put into the atmosphere by the industrial plants stimulated the formation of clouds.

There can be no doubt that the reported weather at La Porte was abnormal during the period after 1920. Some question still remains as to the explanation. Nevertheless, it represents a dramatic example of how man's activity might influence the weather.

It recently has been observed that the lead particles from the tailpipes of motor vehicles may have important effects on ice crystal formation in clouds. We will say more about this in subsequent chapters.

SUMMARY

As man continues to pollute the atmosphere, he is inevitably modifying it, but the degree of modification is still not clear. In view of the possible consequences, however, it is absolutely essential that the atmosphere be kept under constant scrutiny.

4

THE FORMATION OF A CLOUD

The key to the solution of any problem, including control over nature, is understanding. Before nuclear energy could be released by man, it was first necessary to develop an understanding of the atom. Before polio could be successfully combatted, it was essential to learn about the cause and effects of the disease. Before progress could be made in weather modification, man had to acquire some knowledge of how nature governs the weather.

There are some, however, who say we will never be able to control the weather until we have a complete understanding of how it behaves. This position is hard to defend. It was not so with nuclear energy, polio or a great many other advances made over the ages. Look at agriculture, for example. One can hardly say that the function of chemical fertilizers is completely understood. But nevertheless, enough has been learned to bring into being chemical nutrients which have greatly increased the yields of most farm products.

It is evident that the more you know about a phenomenon, the more possible it will be to ascertain whether or not that phenomenon can be beneficially modified. But even with meager knowledge, we can often devise experiments to test whether changes can be brought about. Even if they fail in their primary purpose, they add to the store of information.

Almost all efforts to modify the weather have been aimed at influencing clouds in one way or another. The reasons for this will become obvious in due course. Let us consider what we know, or think we know, about how clouds develop and produce *precipitation*. This is the general term used by meteorologists to designate any form of water or ice particle falling to the ground.

WHAT IS A CLOUD?

If you were to fly with appropriate equipment through a cloud, you would be able to collect samples of cloud droplets on a slide and examine them under a microscope. (You can do this in a fog by merely smearing Vaseline on a glass slide, swishing it through the fog and immediately viewing it under a microscope.) You would find that clouds are made up of millions of tiny spheres of water. They range in diameter from perhaps two to 100 microns.* These minute particles fall very slowly and evaporate rapidly if they fall into clear air. The number in a cubic centimeter ranges from perhaps fifty to several hundred. One hundred per cubic centimeter is a typical value. This may not seem like much, but consider a hypothetical cloud having the shape of a cube one kilometer on the side. It would be a small cloud, but with this concentration it would contain 10^{17} droplets.

Clouds are in sight so often that many times we do not see them all. We don't notice how different they are from one day to the next. Occasionally clouds appear in shallow layers and form thin sheets across the sky. They are called *stratus* or *stratiform* clouds. Sometimes when a cloud is made of water droplets, the sun or moon seen through the mist is closely surrounded by a *corona* of light. At other times the luminary stands at the center of a large, bright ring, an optical marvel called a *halo*. When this occurs you know the cloud is composed of ice crystals.

Stratiform clouds occur at various altitudes and consequently at differing temperatures. Since the air temperature decreases as you go up in the atmosphere (until the stratosphere is reached), the higher the cloud, the colder it is. Fog is a form of stratus cloud appearing near the surface of the earth. When a uniform layer cloud is fairly low above the ground, it simply is called stratus. At medium altitudes, for example, 10,000 feet, a layer

* A micron is a millionth of a meter and equal to 0.000039 inch.

cloud is given the name *altostratus*. If it appears at still higher altitudes, where temperatures are far below freezing, a layer cloud takes the form of a *cirrostratus*. The general term *cirrus* is used to connote a cloud made up of ice crystals.

In the summer it is common to see puffy, cauliflower-shaped clouds. Sometimes they grow vertically to great heights as successive volumes of cloudy air push their way upwards. Under certain conditions the growth continues until an anvil shape appears near the top as cloud matter spreads horizontally. These clouds are in the *cumulus* family. When rain falls from the clouds, they become known as *cumulonimbus*. These are the ones capable of producing lightning and thunder, hail and gusty winds. The term *nimbus* indicates the cloud is precipitating.

The general categories of stratus, cirrus, cumulus and nimbus are combined to form many cloud varieties. We have already mentioned a few. For the sake of this book it is not necessary to introduce any others, but the interested reader can obtain further information by referring to a book on general meteorology.

FORMATION OF A CLOUD

Although the atmosphere always contains some water vapor, clouds occur only some of the time. What conditions lead to cloud formation? First of all, we must explain the condensation of water molecules in the form of small spheres of water. Then it will be necessary to account for the fact that condensation takes place at all.

Condensation is the process whereby a gas is converted to a liquid. Here it means the transformation of a water molecule from the vapor phase to the liquid phase. Condensation is a common occurrence whenever a cold surface exists in the presence of humid air. A glass of ice water usually is wet on the outside. You often hear the expression "the glass sweats." When this happens, water molecules from the air are condensing to a liquid on the side of the glass.

In order to understand the mechanisms of condensa-

tion and evaporation, it is convenient to make use of the concept of *relative humidity*. This expression describes the quantity of water vapor in the air with respect to the amount the air would contain if it were *saturated*.

Imagine that you take a large bottle and pour some water into it. Now put a stopper in the bottle. As soon as the water is put into the container, water molecules begin to leave the water and enter the air that occupies the remaining space in the bottle. At the same time, a smaller number of molecules of water is returning to the water. Since the net flow of water molecules is out of the water, we say evaporation is taking place. As time passes, the quantity of water molecules in the air increases at a slower and slower rate, as illustrated in Figure 4. The

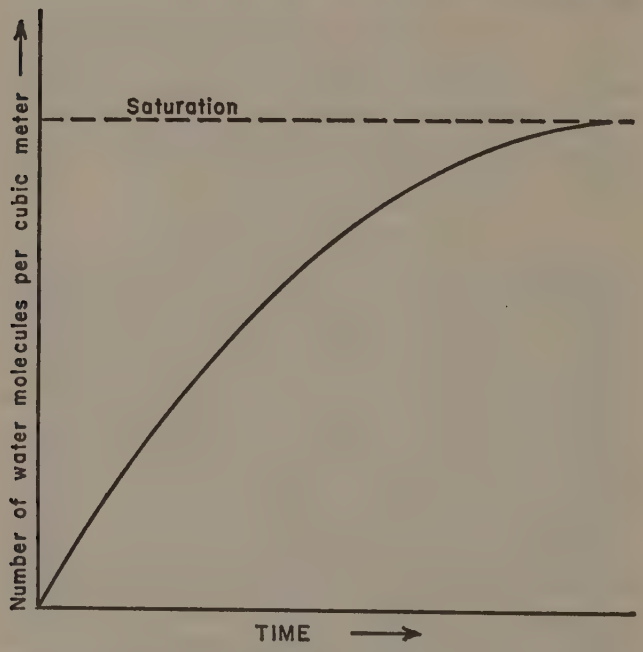

Fig. 4 Increase in the number of water molecules in a closed cubic meter of air.

quantity approaches a fixed value known as the *saturation* value. When the air is saturated, the number of water molecules leaving the liquid is just equal to the number entering it.

At saturation, the relative humidity is exactly 100 per cent. If the number of water molecules in the air is just half what it would be at saturation, the relative humidity is 50 per cent. Most of the time, the concentration of water molecules in the air around us is smaller than it would be at saturation and hence the relative humidity is less than 100 per cent. Under certain special conditions, the air may contain more water molecules than the value at saturation. When this happens we say that the air is *supersaturated.*

The concentration of water molecules corresponding to saturation depends on air temperature. The higher the temperature, the more water is needed to saturate the air. This means that if the amount of water vapor is constant, the higher the temperature, the lower the relative humidity. As a result, relative humidities generally are lower in mid-afternoon than in early morning hours.

Let us return to the example of the closed bottle containing air saturated at a temperature which we might take to be 20° C. Imagine now that the temperature of the bottle and its contents is lowered *suddenly* to 15° C. At this point, the air becomes supersaturated. The water molecules which saturated the air at the higher temperature cannot instantly return to the water. Instead, they begin condensing on all available surfaces, on the water, to be sure, but also on the inner surface of the bottle. If the cooling took place fast enough, condensation might also take place on solid particles suspended in the air.

In the atmosphere a similar course of events occurs when clouds are formed. When some process occurs by which a body of air is cooled, its relative humidity may exceed the saturation value. Water molecules will seek to leave the air and condense on something. The air contains large numbers of tiny solid particles. They become the nuclei for cloud droplets. As condensation takes place, cloud droplets are produced. For obvious reasons, the particles

on which the water condenses are called *condensation nuclei.* They are mostly the products of smoke, blowing soil and sea salts thrown up from the oceans.

If there were no condensation nuclei, we would have far fewer clouds. As a matter of fact, if the air were perfectly clean, water droplets would not form unless the relative humidities were several hundred per cent. This means the air would have to be cooled much more than is the case in the natural atmosphere. As it is, the relative humidity seldom exceeds 102 per cent, and even that requires rapidly rising air, cooling at an unusually fast rate.

The most effective condensation nuclei have an affinity for water vapor, and the air around them becomes saturated even when relative humidities are below 100 per cent. In the case of certain sea salts, condensation occurs when relative humidities reach about 70 per cent. As you know, on humid days salt shakers sometimes become ineffective because the salt refuses to come through the holes. When this happens, blame it on the small quantities of water condensed on the salt grains. The wet particles stick together.

Thus the ingredients for clouds are water vapor, condensation nuclei and a cooling mechanism. There are several cooling mechanisms in the atmosphere leading to condensation and cloud formation. For example, the tiny water droplets in fogs are produced when humid air near the ground is cooled. This takes place when heat from the ground is radiated toward outer space. The loss of heat occurs most rapidly on clear nights. As radiation proceeds to transfer heat upwards, the ground and air temperatures fall and the relative humidity of the air rises. The cooler air is heavier and tends to sink into the lower places, such as valleys and dips in the road. If temperatures drop low enough for relative humidities to approach saturation, condensation takes place on nuclei in the air. Sometimes only patches of fogs appear. On a highway, they become potentially lethal hazards to motorists. At times fog may cover large parts of several states.

Fogs may also be produced when warm, humid air passes over a cold land or water surface. In this case,

heat is lost from the air by conduction and radiation. If the air is sufficiently cooled, condensation occurs and a fog appears.

Because of the smallness of fog droplets, the quantities of precipitation produced by fogs are very small and for the most part of negligible economic importance, but this is not always true. In certain parts of the world, such as mountainous regions with high fog frequencies, fogs play an important role in maintaining plant life. As the air containing the droplets passes through the trees, the droplets impinge on the leaves and branches. The water accumulates, wets the plant and then drips to the ground. Pine needles are particularly good collectors of small water droplets.

Most precipitation reaching the ground falls from clouds having relatively large vertical extents. These clouds do not form because the air loses heat, but rather because the air rises and cools as it expands. It may seem strange at first, but air can be cooled even though it does not lose heat. The explanation lies in the fact that the cooling comes about as a result of loss of energy, and heat is only one form of energy. Because of the importance of this concept, some elaboration is probably appropriate.

We know that atmospheric pressure decreases with altitude. Hence, if a given mass of air ascends from one level to a higher one, the pressure on its boundaries decreases. As a result, the air expands and the volume occupied by the mass of air increases. Imagine that the mass had the shape of a sphere. In expanding, the surface of the sphere would move outward. Some work would have to be done on this movement. In order to do work, energy is required. The energy comes from the original mass of air. The loss of energy is manifested as a reduction of temperature.

The process whereby the temperature of an expanding body of air is decreased without loss or gain of heat is called an *adiabatic process*. The rate of temperature change can be calculated. In the earth's atmosphere it equals 1° C per 100 meters of altitude change. Ascent and expansion lead to cooling; descent and compression lead to warming.

Imagine that a stream of air moves against a mountain barrier. As it is forced upwards, it cools 1° C for every 100 m of rise. As its temperature falls, its relative humidity increases until the air becomes saturated, at which point condensation occurs and a cloud forms. As the air continues to go up, it continues to cool, but at a slower rate than the adiabatic rate because condensation causes heat to be released. The origin of this heat can be traced back to the evaporation of water.

Consider for a moment how water molecules get into the atmosphere. As we know, they do so as a result of evaporation from the ground, plants, animals and mostly from the large expanse of oceans. In order to dislodge a molecule of water from the water surface, energy is required. The chilling you feel when stepping out of a swimming pool on a dry day indicates your body is giving up energy in the form of heat as the water evaporates. The quantity of heat required to evaporate a unit mass of water is called the *latent heat of vaporization*. Its magnitude is about six hundred calories per gram of water.

According to the dictionary, the word "latent" means "lying hidden and undeveloped within a person or thing." In a sense, a gram of evaporated water has about six hundred calories of heat "lying hidden or undeveloped" within the water molecules in the air. When these molecules are condensed, the heat is released and acts to warm the region where condensation occurs.

As an example, imagine that one tenth of a gram of water vapor condenses to form a cloud in a one cubic meter volume of air located at an altitude of about 10,000 feet. During condensation, sixty calories of heat are released into the air $\left(\frac{1 \text{ gram}}{10} \times \frac{600 \text{ cal}}{1 \text{ gram}}\right)$. This quantity of heat would raise the air temperature by about 0.3° C.

Now return to the case of the air ascending along the mountain slope. Before condensation began, the rising air was cooling 1° C per 100 meters. (See Figure 5.) Meteorologists would say that the *temperature lapse rate* was 1° C/100 m. In the case of ascending or descending air,

you can be more specific and call it the *dry adiabatic lapse rate.*

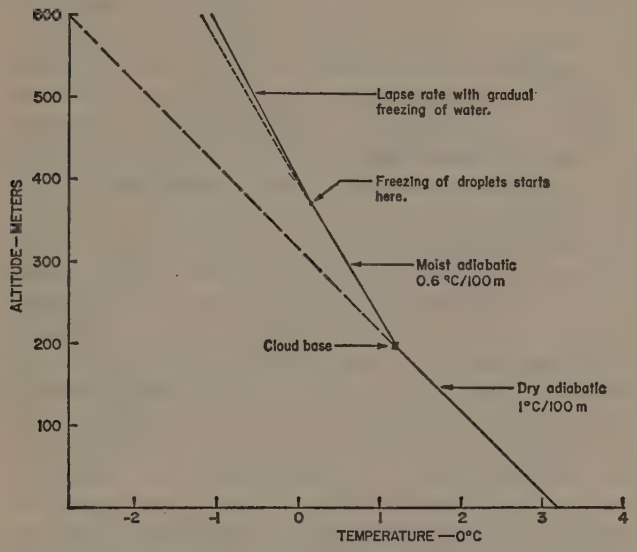

Fig. 5 Changes of temperature of a rising mass of air. See the text for an explanation.

After condensation begins, the released latent heat of vaporization is added to the air. As a result, the rate of temperature change is reduced (Figure 5). The expression *moist adiabatic lapse rate* is employed to designate the rate of temperature change in a rising body of air in which condensation is occurring. A typical value for the moist adiabatic lapse rate is 0.6° C/100 m. The magnitude in any case depends on the temperature and pressure of the air.

Let us assume that the cloudy air continues to go higher and higher until it passes above the freezing level. When the water droplets change to ice particles, more heat is released into the air. The proper name for this heat is the *latent heat of fusion.* It has a magnitude of about ninety calories per gram of water. It may surprise you to realize that heat becomes available when freezing occurs. How-

ever, you certainly are aware that heat is needed for melting ice. The speed at which an ice cube melts depends on how much heat is supplied to it. The water takes up heat as the ice melts. In a sense, the heat "lies hidden" in the molecular structure of the water, ready to be released when the water freezes again.

When the droplets in a rising volume of cloudy air are freezing, the temperature of the air cools at a rate even slower than the moist adiabatic lapse rate. This is illustrated in Figure 5. If no condensation and freezing took place, the ascending air would cool off at the rate indicated by the dashed line. Note how much warmer the air is at the higher altitudes as a result of released latent heat.

We have dwelled at some length on the subject of lapse rates and latent heats for an important reason. Much of the power for driving the atmospheric "engine" comes from these sources of energy. And as with any engine, one possible means of tampering with it is through its energy supply. More will be said on this subject in later chapters, but a simple calculation will illustrate how important latent heat is.

An ordinary thunderstorm can produce 100,000,000 kilograms (about 100,000 tons) of rainfall. The latent heat released during the condensation of this water would be 10^{11} grams $\times \frac{600 \text{ cal}}{1 \text{ gram}} = 6 \times 10^{13}$ calories. This is roughly equivalent to the energy of three twenty-kiloton atom bombs of the type used at Nagasaki. From large thunderstorms, ten to 100 times more rain can fall. In the case of hurricanes or cyclones, the total quantity is much greater. These are truly fantastic quantities of energy. They illustrate that short of using nuclear explosives, we cannot hope to modify storms by brute strength. We must find other ways to attack them.

STARTING THE UPDRAFT

Since rising air is needed to produce clouds, let us consider how updrafts are established in the atmosphere. The effects of a mountain ridge are easy to visualize. The air

moves up the slope because it has no other place to go. A similar effect occurs when a large body of warm air moving from the south encounters colder air moving from the north.

Cold air is relatively heavy. We say that its *density*—the mass of air per cubic centimeter—is high. Warm air is relatively light. The density of air decreases as its temperature increases. Also, the more water vapor in a body of air, the lower its density, because a water molecule weighs less than an air molecule. As cold, dry heavy air encounters warm, humid and hence less dense air, the two air masses do not readily mix. The cold air moves under the warm air in the form of a wedge. (See Figure 6.) The boundary between the two air masses is called a *front*. As a front advances, it forces the warm air to rise and may lead to clouds.

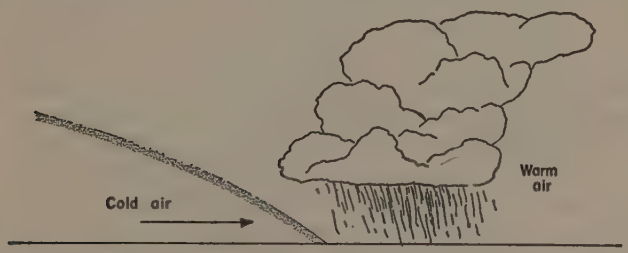

Fig. 6 The boundary between advancing cold air and warm air is called a front.

There are various types of fronts, and almost all cause ascending air in one form or another. Some of them are characterized by slowly rising air covering areas several hundreds of miles in diameter. This leads to layers of clouds from which rain or snow may fall. When cold air advances rapidly against warm, moist air, the effect can be regions of strong updrafts with the production of lines of showers and thunderstorms.

Sometimes widespread clouds and precipitation occur where there are no fronts. When this occurs, the explanation can usually be found in the wind and atmospheric pressure patterns. A common cloud-producing pattern is

one where there is a so-called "trough" in the pressure field (Figure 7[a]). This is a roughly north-south zone, along which the pressure is less than it is on either side. To the west of the trough line the winds are generally from the northwest. At the trough they swing into the west. To the east of the trough line they move from the southwest. This type of wind flow leads to so-called "convergence" on the east side of the trough where the winds slow down. As a result, some of the air rises (Figure 7[b]).

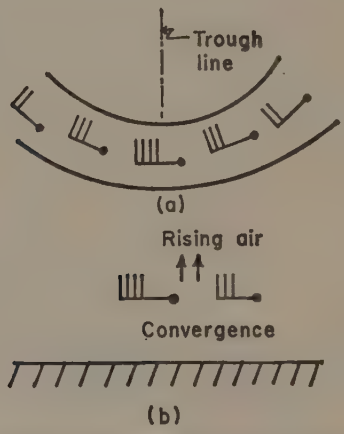

Fig. 7 (*a*) *Wind velocities through a "trough line" in the pressure patterns. The arrows show wind direction and speed at dotted points. The greater the number of barbs, the higher the wind speed.*

(*b*) *Just to the east of the trough line, the winds decrease in speed. The air converges and rises.*

In layer clouds, the air may rise at speeds of 0.1 to 1 meter/second, but in thunderstorms, updrafts often are greater than 10 m/sec and sometimes may exceed 50 m/sec. These tremendous speeds can come about only when the air is *unstable*. By this, we mean that the temperature decreases rapidly with height. When it does, a volume of rising air can remain warmer than the air surrounding

it. Under this circumstance, it will be lighter than the air around it, and continue accelerating upwards.

Many thunderstorms occur as more or less isolated regions of rising air. These local thunderstorms are seen to be somewhat randomly scattered over the countryside. Observations by means of radar and high-flying aircraft or satellites show that they are more likely to occur over sun-heated land than over water surfaces. "Hot spots" in the land, where temperatures are warmer than in surrounding areas, are favorite spawning grounds for thunderstorms. Heat is transferred from the ground to the air. Since warm air is lighter than cool air, vertical air currents are set up. We say that *convection* begins. The warm air rises and, in the process, it transfers heat upwards. At the same time, the rising air cools as it moves to higher altitudes. If it cools sufficiently to result in cloud formation, the resulting clouds are called *convective clouds.*

The role of the sun's heating in setting off the growth of convective clouds is clearly illustrated in mountainous regions. In Arizona, for example, showers and thunderstorms are more numerous over the mountain ridges than over the valleys. But the storms are not equally frequent day and night. Commonly, the morning hours are free of clouds. They develop after the sun has warmed the peaks and slopes enough to initiate updrafts. As a result, showers usually do not begin until early afternoon. Once they start, they may continue on into the evening hours as existing thunderstorms set up air motions leading to new storms.

SUPERCOOLING AND ICE CRYSTALS

Earlier we stated that when clouds become cold enough, water droplets freeze and ice crystals form. The question of how cold is "cold enough" is a crucial one to cloud physicists. Equally important are the mechanisms by which particular types of ice particles are produced in the atmosphere.

In the schematic drawing of Figure 5 showing temperature lapse rates, we indicated that freezing begins when the air becomes colder than 0° C. This was done to sim-

plify the discussion. In fact, in an ascending cloud, the droplets seldom freeze at 0° C (32° F). The water droplets can be carried to very low temperatures and still remain in liquid form. When the droplets are liquid at temperatures below 0° C, they are said to be *supercooled.* It is common, especially in rapidly building clouds, to find supercooled droplets at temperatures below −10° C, and liquid droplets have been observed even at temperatures as low as −35° C. In laboratory experiments, very minute water droplets have been cooled to close to −40° C.

For someone living in the frigid climate of northerly latitudes where ice on the street is a common occurrence, the concept of supercooling may be hard to understand. Certainly a small puddle of water in the street turns to ice whenever the temperature drops below 0° C. The secret of supercooling lies in the purity of the water. When careful distillation is performed to remove all, or almost all of the impurities in water, supercooling is possible. And that is what happens in the atmosphere as a cloud forms. Each droplet forms on a tiny condensation nucleus as water vapor is distilled on it. As long as there is some supersaturation, the condensation of water molecules continues. When a cloud droplet reaches a diameter of ten microns, it is composed of very clean water.

Have you ever thought of how an ice crystal begins to grow? Certainly if you have ever examined an hexagonal crystal or the pattern of ice on a frozen window in the winter, you get the impression of organized growth. You can almost visualize each molecule being set in place, one at a time. Much as a bricklayer constructs an intricately designed wall, the water molecules are arranged to produce complex and often beautiful crystals. But how does it all begin?

As do water droplets, ice crystals require a nucleus on which to grow. This is the case except when the temperature is unusually low. The nuclei are of a different character than those which act as good condensation nuclei and consequently go under a different name. They are called *ice nuclei.*

A great many substances found in the atmosphere can

serve as ice nuclei, but they are not all equally effective. Some lead to ice crystals at temperatures of perhaps −10° C; others will not work until temperatures are below −20° C. A number of scientists have studied the ice nucleating properties of various types of minerals, clays and organic substances. They also have asked themselves which substances are likely to be found in the atmosphere in sufficient abundance to account for the fact that, in general, clouds freeze before they reach −15° C. It is the judgment of most scientists who have studied this subject that most natural nuclei are tiny clay particles carried upwards by the wind. They are found to be effective at temperatures between −10 and −15° C.

Not everyone agrees that the surface of the earth is the source of most of the natural nuclei. A notable objector to this idea is E. G. Bowen of Australia. He has maintained the position that the ice nuclei are composed of meteoritic dust brought into the atmosphere as the earth sweeps around in its celestial orbit. He and his colleagues have published some evidence in support of his hypothesis, but it has not been convincing enough to shake the opinion of most cloud physicists that the earth is the major source.

Whatever the origin of natural ice nuclei, it is clear from measurements made all over the world that they are not uniformly dispersed. Many observations have been made of the concentration of nuclei effective at −10 to −20° C. The quantities vary widely in time and space. The variations can also be recognized by observing clouds and noting whether or not they are supercooled and at what temperatures. The presence of supercooled clouds is indicative of an inadequate supply of natural nuclei.

In 1946, Vincent J. Schaefer showed that artificial nuclei could do what nature sometimes is incapable of doing. This was the first crucial step in the development of a scientific approach to cloud modification. We shall examine the details of Dr. Schaefer's work and that of his colleagues in due course.

5

RAIN AND SNOW

Very few people have had the opportunity to see individual cloud droplets under a microscope, but everyone has seen raindrops hit the ground. By definition, a raindrop is a drop of water greater than 0.2 millimeter (about 0.008 inch) falling through the atmosphere. The smallest raindrops occur during a drizzle, a type of rain which generally produces only small quantities of precipitation. Most rains contain drops having diameters greater than about 1 mm. Raindrops seldom are greater than 8 mm in diameter, because when they become this large they break up and become many smaller drops.

Cloud droplets grow by condensation, but the process does not go on and on. When a mass of humid air rises, the first water droplets form on the larger, more effective condensation nuclei. As these droplets become bigger, the water of which they are composed becomes purer and condensation slows down. As this occurs, condensation starts on smaller nuclei. The available water vapor in this way is distributed among so many droplets that none of them becomes large enough to become a raindrop. By condensation alone, cloud droplets usually will be restricted to diameters below 0.1 millimeters (about 100 microns). Since raindrops typically have diameters much larger than this, some other process must be involved. We know of two of them.

COALESCENCE PROCESS

Some clouds are composed of water droplets having diameters smaller than perhaps twenty microns. Such clouds are stable and incapable of producing rain under normal circumstances. In some clouds, however, droplets having diameters close to 100 microns can occur. These

large water drops can be formed by condensation when giant sea salt particles are carried into the cloud. There are other ways by which large droplets may be produced. Regardless of how they come into being, they can have a profound effect on the cloud.

The larger the cloud droplet or raindrop, the faster it falls. A 100-micron droplet will fall faster than the much more numerous ten-micron droplets in a typical cloud. The big droplet collides with the smaller ones and grows as the droplets merge. This process is called the *coalescence process*. The larger the rapidly falling drop, the faster it grows; the larger it gets, the faster it falls, and so forth.

It has been found from laboratory experiments that if water droplets are not under the influence of electrical forces, they often bounce off one another. Some high-speed movies show the smaller of the drops depressing the surface of the bigger one and flying outwards like a gymnast on a trampoline.

When colliding droplets are electrically charged or in the presence of a sufficiently high electric field, coalescence occurs almost every time. Doyne Sartor at the National Center for Atmospheric Research, who has studied this effect for a number of years, has offered some speculations on this result. He has suggested that, as the droplets hit, coalescence is prevented by a thin layer of air between the water surfaces. Electrical forces can cause a breakdown of the air layer and lead to coalescence. Most cloud physicists seem to be of the opinion that clouds having other rain-producing characteristics usually have sufficient electric fields to cause virtually all colliding drops to coalesce.

Bernard Vonnegut at the State University of New York at Albany, and his colleague Charles B. Moore, now at the New Mexico Institute of Mining and Technology, have proposed some new ideas on the importance of electrical effects on rainfall. They have argued that in thunderstorms, electrification precedes the formation of precipitation and that lightning leads to electrical forces causing very rapid coalescence and precipitation formation. In a sense, these are revolutionary notions. Not many cloud

physicists have yet joined the rebellion, but it must be admitted that all the evidence is not in. The uncertainties in this critical problem stand as commentaries on our inadequate understanding of the details of the rain process.

In tropical areas, the coalescence process certainly accounts for much of the rainfall. Many clouds whose tops never become colder than 5° C produce showers. Moving northward, especially over land areas, there are some important changes in the characteristics of clouds, particularly of cumuliform clouds. Over the Caribbean waters their bases are generally about 2,000 feet above sea level. Over the Middle West, they usually are nearer to 5,000 feet. In the more arid southwestern regions of the United States, they are found near 10,000 feet. In these dry areas, the clouds seldom produce rain until their tops are substantially colder than 0° C. Supercooling is common. Ice particles in the upper regions of precipitating clouds also are common.

ICE CRYSTAL PROCESS

In the winter, precipitation in the form of ice crystals and snow falls from stratified clouds. An examination of the frozen particles often shows that they did not form as a result of the freezing of big water drops. Instead, they can only be explained as ice crystals which grew by the deposition of water molecules from the vapor to ice phase. This is a process very different from the coalescence process. For this reason, it is given a different name —the *ice crystal process* or the *Bergeron-Findeisen process*. Tor Bergeron is a Scandinavian meteorologist who in the early thirties proposed the fundamental ideas involved. W. Findeisen was a German scientist who made important contributions to the understanding of the growth of precipitation.

A cloud composed entirely of water droplets, supercooled to say −10° C, may exist for long periods of time with little change. On the other hand, if some ice crystals fall into the supercooled cloud, its cloud properties change drastically. This was the fact first recognized by Ber-

geron. He pointed out why ice crystals grow while the water drops evaporate. The reason is based on the physical properties of ice and water.

We mentioned earlier that when air over a water surface is saturated, the number of water molecules leaving the liquid just equals the number entering it. The density of water molecules needed to saturate the air over ice is smaller than it is over supercooled water at the same temperature. Therefore, when ice crystals occur within a supercooled cloud, the air contains more water molecules than are needed to saturate the air over the ice crystals. In such a situation, water molecules deposit themselves on the ice, leaving a deficit in the air. Some water evaporates to make up the deficit. This makes the air supersaturated again with respect to ice and more molecules deposit on it. In this manner, existing ice crystals may grow rapidly. The most rapid growth takes place at a temperature of about −12° C.

An ice crystal may grow to a size equivalent to a 200-micron droplet in a period of several minutes. As its mass increases, it begins falling faster than the surrounding particles. In falling it sails back and forth like a leaf in the wind. As a result, it may encounter supercooled drops, which freeze on impact. Collisions with other ice crystals lead to snowflakes as the individual crystals stick together.

When temperatures are below freezing all the way to the ground, the frozen particles reach the earth as snow. If the temperatures are warmer than freezing, the falling particles may melt and produce rain. In mountainous regions there is often snow accumulating on the ridges while rain wets down the valley.

If an ice particle finds itself in a thunderstorm having a strong updraft, it can spend a relatively long time in a supercooled cloud. The uprushing air can virtually suspend it above the ground as cloud droplets splatter on it. As the supercooled water coats the ice kernel and freezes on it, a hailstone can be born.

As long as hailstones remain in a supercooled cloud, they continue to grow. In some storms they may reach the mammoth size of oranges. Usually they are smaller

than a centimeter in diameter. The bigger the stones, the more destructive they become when they bombard fruit orchards, fields of grain or even the tops of automobiles. Even stones the size of marbles, however, can flatten a wheat field if enough of them fall to the ground.

We suspect that some hail exists in the upper part of most thunderstorms. Fortunately, the particles are small and melt before they reach the ground. Melted hail particles can account for the very large raindrops you sometimes see under a thunderstorm.

Actually, hailstones melt quite slowly. According to calculations by the English cloud physicist B. J. Mason, even as small a stone as one having a diameter of 0.5 cm has to fall more than 13,000 feet below the freezing level before it completely melts. This is about the height of the 0° C level above the ground in regions where hail is common. Therefore, if stones in the clouds are greater than about half a centimeter in the supercooled part of the cloud, some ice may reach the ground. The bigger the stone, the more of it will be left when it hits the earth.

MANIPULATING NATURE

In the last two chapters we have outlined briefly present conceptions on the natural mechanisms for the formation of clouds and precipitation. Many aspects of these mechanisms are still somewhat mysterious. We cannot yet write out equations describing, in adequate detail, the growth of a cloud and the subsequent development of rain, snow or hail. This is not to say we are totally in the dark. Some parts of the picture are reasonably well in focus. Other parts, needed to synthesize the whole, still await elucidation.

As you read about the physics of clouds, rain and snow, you probably thought of several means by which it might be possible to manipulate them. At this point, only a few will be mentioned. They will be examined in more detail as we go along.

First of all, it does not seem at all practical to try to control the atmosphere by brute strength. The energies of

most storm systems are so large that only the use of atomic bombs might have some effect, and the subsequent radioactive fallout would pose dangers far greater than the benefits likely to accrue.

If we wish to influence the atmosphere, it is necessary to find some instabilities, some "soft spots," where a small input of energy will lead to ever-increasing effects. We know that some such instabilities exist.

When a cloud forms, the occurrence of rain or snow depends on the presence of certain types of nuclei. Sometimes there is a deficiency of giant condensation nuclei or ice nuclei. In this case the cloud passes through its life without producing particles large enough to reach the ground. When nature is deficient in natural nuclei, it is possible to introduce artificial ones. This is called *cloud seeding.* In certain circumstances, ice nuclei dispensed in supercooled clouds have produced dramatic effects. For example, airports have been cleared so that airplanes could land and take off.

In some convective clouds, because of unstable atmospheric conditions, small quantities of heat may lead to accelerated cloud growth. Large doses of ice nuclei in the supercooled parts of certain convective clouds can cause the release of the latent heat of fusion and increase the cloud's vertical extent.

Ice nuclei have been employed in experiments aimed at reducing the size of hailstones. If the number of stones were greatly increased, the result would be smaller stones. If they were sufficiently small, they would melt and reach the ground as rain.

It has been proposed that by converting supercooled droplets to ice crystals, it might be possible to change the characteristics of the rain. For example, in some instances it would be desirable to make it fall sooner or for a longer period of time so that torrential downpours could be prevented.

Many scientists believe that the production and separation of electric charge in thunderstorms comes about because of the interaction of supercooled water and ice

particles. If this is so, and if the supercooled state can be influenced, perhaps lightning could be diminished.

We know that snow particles are composed of ice crystals. Can you make more snow fall by adding ice nuclei to the atmosphere at the right time and place? Wouldn't it be great if clouds could be seeded in such a way as to make snow fall over the watersheds, but not in the cities? Think how grateful the people of New York, Chicago, Montreal, Berlin and Moscow would be if they could be relieved of the job of moving thousands of tons of snow. Some people have looked to cloud seeding as offering some hope. At this point, we suggest that you keep your snow shovel in good repair. At least for a few years into the future, snow will continue to fall mostly where nature and chance choose to put it.

6

CLOUD CREATION

The realization that heating of the air at the ground leads to clouds goes back a very long time. This naturally has inspired a number of people to suggest schemes for giving nature a hand.

One of the best-known ideas was proposed in 1850 by the American meteorologist James P. Espy. He spent many years studying the formation of clouds and rain and made some important findings. In particular, he was the first to recognize that the released latent heat of condensation played an important role in the growth of convective clouds. Espy also recognized that clouds often fail to develop because of the absence of upward air motion. This led him to propose a research program of truly heroic proportions. In the jargon of today we probably would put it in the class of "big science."

Espy suggested that lines of summer convective clouds could be produced by burning large masses of timber. He had in mind about forty acres every twenty miles along a north-south line some six to seven hundred miles long. Furthermore, he proposed that the burn be repeated every seven days. He visualized that the fires would set up lines of cumulonimbus clouds which would propagate eastward, wetting down the country as they traveled to the Atlantic Ocean.

Although Espy did not promise beneficial results, he did regard them as highly probable and asked Congress to appropriate funds to try some experiments. This, of course, was long before the day of governmental enthusiasm for supporting research, and his request was denied.

MAKING CUMULUS CLOUDS

Some one hundred years after Espy, Dr. Henri Dessens, a French cloud physicist working in tropical Africa, be-

came intrigued with the idea of inducing clouds to form by heating. Apparently, the sight of cumulus clouds over brush fires started him thinking about this problem.

Dessens reasoned that it might be possible to produce clouds by using solar energy. His first experiment involved clearing a small area (0.08 square mile) of equatorial forest. He recognized that the cleared ground would become warmer than would the wet, thick vegetation surrounding it. When winds were light, small cumulus clouds did form over the heated soil, but they did not produce any rain. He decided that it would be necessary to use a larger area and to add more heat than that supplied by sunshine.

Dessens second series of experiments was a small-scale version of those proposed by Espy. On days appearing favorable for cloud formation, he carried out controlled burning of the vegetation. He was ". . . immediately struck by the ease with which in the equatorial regions, large cumulus clouds can be obtained by this method. . . ."

Dessens was so pleased with the results that he proceeded to develop a still more controlled method of heating the air. He coined the word "meteotron" to designate any experimental arrangement capable of initiating convection leading to rain-producing clouds. He proceeded to devise a system of some 100 oil burners placed around a circle about 250 meters in diameter. (See Plate 7.) At the appropriate time of day (perhaps 30 minutes before large convective clouds would form naturally, according to Dessens), the oil burners are simultaneously lighted, producing a thermal impulse of about 800,000 kilowatts. He has reported that the meteotron has successfully produced clouds and his experiments have supplied information on the energy required to initiate cloud formation in the atmosphere.

The evidence on hand does not indicate that the meteotron has been employed to bring about practical increase in rainfall. Nevertheless, Dessens appears to be convinced of its utility for the study of clouds. In 1968, he built a meteotron composed of sixty burners, putting out as much

heat as the 100 he had used earlier. In 1966, Dessens reported on a trip to Cuba along with several Russian meteorologists. They were there to advise the Cuban Government on the establishment of a program of atmospheric research. Part of this program included the use of a meteotron.

Dessens first felt that heating by the sun's rays would be enough to start convection, but later decided that additional energy was needed. A group of scientists of the research staff of the Esso Research and Engineering Co., however, have tried to make a case for the use of solar energy. James F. Black and his associates have proposed coating the ground with asphalt to absorb the sun's rays. They argue that the warm asphalt will heat the air enough to cause clouds to form and rain to fall. However, it has yet to be shown that this will lead to rainfall increases. To date there have only been speculations based on somewhat oversimplified calculations. Nevertheless, the idea may have some promise and is getting continued study.

In 1965, Black indicated that plans were underway to make some field tests in the coastal desert of West Australia. Strips of desert soil were to be blackened with asphalt and interspersed with rows of rocks and other debris. The reason for the latter is to stir up the air and hopefully start updrafts.

Surely the asphalt will get warmer than the surrounding lighter ground. But will the resultant heating lead to clouds? And even more important, if there are clouds, will they be rain producers? Or will it be found, as Dessens found earlier, that you need even more heat than the heat of the sun's beams?

In 1958, Dr. Florence W. van Straten and her fellow meteorologists at the Naval Research Laboratory near Washington, D.C. came up with an ingenious scheme for modifying clouds. As had others, she reasoned that it might be possible to harness some solar energy for cloud making. Unlike earlier investigators, who worked at the ground, however, she took to the air. Her technique consisted of dispersing finely powdered carbon particles from an airplane. It was reasoned that these black particles

would absorb the sun's rays and thereby heat up the air. If sufficient heating could be produced, the air would become buoyant and start to rise. If the atmosphere were unstable and moist, the ascent would continue at an accelerated pace and a cloud could be formed.

Working with tiny carbon particles can be a messy business. The author witnessed an experiment being conducted in Arizona in about 1959. A crop-duster pilot with his own airplane was doing the carbon seeding under contract with the Air Force. The aircraft was an old biplane with open cockpit. The whole operation looked like a scene from a World War I movie. The pilot wore an old-fashion leather flight helmet with goggles. Everything was coated with black—the airplane, the pilot and his helmet.

For a few years the carbon black idea was investigated both theoretically and in the field. Dr. van Straten reported some success in a small number of experiments in late July 1958, but little has been heard about it recently and one suspects the merit of the idea.

CONTRAILS

Strictly by accident, man has developed one very effective method for producing clouds. Almost everyone has seen the result at one time or other. They appear high in the sky and are called *contrails.*

The fuel used in airplane engines is not completely burned. Out the tailpipe comes a variety of gases. One of them is water vapor. As Herbert Appleman of the Air Weather Service pointed out in 1953, this water vapor can lead to cloud formation.

An engine exhausts heat as well as water vapor. The heat acts to lower the relative humidity of the air; the water vapor, to raise it. When temperatures are quite low, the latter overcomes the former. As a result, the relative humidity is raised until the air becomes saturated. This happens very fast and condensation takes place just behind the airplane. If you have not already realized it, the word contrail comes from "condensation trail."

In order for contrails to form, it is necessary that the airplane be flying at a low temperature, certainly below −30° C. For this reason, contrails usually are associated with jet airplanes flying at high, cold altitudes.

Initially, a contrail is composed of tiny water droplets produced by the condensation of water vapor on nuclei. But at the low temperature prevailing at contrail altitudes, the droplets rapidly freeze and leave a thin streamer of ice crystals. The duration and behavior of a contrail depends on the relative humidity of the environment through which the airplane is flying. Often the relative humidity is low. As a result, the contrail evaporates fairly quickly as dry air mixes with it. When this happens, you see a short line of white behind a single-engine airplane. If it has more engines, you see several contrails parallel to one another.

When the relative humidity is moderately high, contrails may last for many minutes. Sometimes you see them change shape under the influence of varying winds. Occasionally, when the air is very humid, contrails can persist and spread outward horizontally. In some instances, the end result is a layer of cirrus clouds covering almost the entire sky.

Contrails are produced when the relative humidity of the air is increased by adding water vapor to it. Another way to raise the relative humidity is by lowering air temperature. In the late forties, scientists at General Electric Company were the first to show this could be done. They dispensed pellets of Dry Ice from a high-flying airplane. The Dry Ice, having a temperature of about −70° C, cooled the air enough to cause streamers of ice crystals to form. The result was a cirrus cloud. (See Plate 8.)

Cirrus clouds by themselves do not rain, so those produced by contrails will not have a direct effect on precipitation. Sometimes, though, they may seed supercooled clouds below them with ice crystals and thereby lead to rain or snow. Decks of ice crystal clouds can also have an indirect effect on water supplies by shading the ground. Especially in desert regions, even a slight shadow can mean a temperature drop of several degrees. This, in turn,

reduces the need of water for cooling living organisms. No one has yet suggested seriously that we try to create and use contrails on a practical basis, but they stand as irrefutable evidence that man can produce clouds.

Interestingly enough, the military services have been disturbed by contrails. A high-flying airplane is very difficult to see. Of course, when it trails a line of glistening white cirrus like a banner, it becomes visible to all. Not only does the contrail show the airplane's position, but it allows its flight direction to be immediately read and its speed estimated. For this reason, much research has been devoted to the development of a procedure for preventing the formation of contrails. It has been found that adding certain substances to the fuel can reduce the number of contrails by retarding condensation and allowing the water vapor in the exhaust gases to mix in its gaseous state with environment air. Is it not ironical that clouds so easily produced are not wanted, while those so much in demand elude our inventions?

So where do we stand today? There still is no scheme for producing clouds from which practical amounts of rain can be wrung. The meteotron is a laboratory device, a large one to be sure, but still a device for studying convection, not for solving water shortages.

Our inability to devise a practical technique for cloud making does not mean that such a procedure does not exist. Perhaps it is still awaiting discovery. Conceivably, by the time you read these lines some inspired atmospheric scientist may have had a flash of brilliance and found a way to do it. Until such a happening, it will be necessary to take clouds as they come and try to manipulate them in useful ways.

7

CLOUD MODIFICATION

We already saw how difficult it is to make a cloud. Is it equally hard to destroy one? Not quite. As a matter of fact, in some cases it is relatively easy.

In considering ways to *dissipate* clouds, to use the term common among meteorologists, it is appropriate to consider several classes of clouds. Water clouds with temperatures higher than 0° C are called *warm clouds*. Secondly, there are supercooled clouds, both stratiform and cumuliform. Cirrus clouds, those composed of ice crystals, constitute still another category.

Almost no work has been done to dissipate cirrus clouds and hence little will be said about them.

WARM CLOUDS

In many regions of the world, fog and low stratus constitute a frequent hazard to aviation. Flight delays, cancellations and diversions cost U.S. airlines an estimated $75 million a year. In a place such as London, the fog problem is particularly serious. American flyers operating out of England during World War II became acquainted with the problem firsthand. It was particularly severe then because the landing systems were crude compared with those available today.

Even with the most modern radar sets and other electronic devices, it still is necessary that the cloud ceiling (the height of the cloud base above the ground) and the visibility be above certain minimums. Typical figures are a ceiling of two hundred feet and a visibility of one half mile. When conditions approach "zero-zero," as they do with a dense fog, landing is out of the question. A takeoff might be attempted by a courageous pilot on a mission of the utmost urgency. But the risks would be great indeed.

The need to develop means for clearing airports spurred research on fog dissipation during the early forties. A number of schemes were tried. Chemicals such as calcium chloride were dropped into clouds in attempts to cause condensation and fallout of the water droplets. Some effects were observed, but this technique was not found to be practical.

The idea of using salt, of the common household variety in this case, was re-examined in 1967 by scientists at Cornell Aeronautical Laboratory. They proposed that if carefully sized salt particles are seeded into clouds, total quantities amounting to several hundred pounds might clear the fog over an airport sufficiently to allow aircraft to operate. The object of the salt seeding is to increase fog droplet diameters and to reduce the number of drops, and hence to increase the visibility through the fog.

During 1968, the Air Transport Association financed the testing of some new substances for clearing fog. Certain chemicals provided by Dow Chemical Company and Proctor and Gamble Company were dropped into fogs or blown into them from the ground. The properties of the chemicals were not released to the public as of 1968. The materials are supposed to cause the fog droplets to coagulate, become larger and fall to the ground. Although certain airline officials involved with the experiment issued optimistic statements, there was still skepticism among most cloud physicists. The general feeling was that the tests conducted could be interpreted in various ways.

In discussing the formation of a cloud, we mentioned that condensation takes place when moist air is cooled. It follows that when cloud air is warmed, the droplets evaporate. This is the basis for a workable scheme, developed during World War II, to dissipate fog over runways. It is generally called FIDO, which stands for Fog Investigation Dispersal Operations. In this system, as it was originally used, kerosene or other fuel burners were located along runways. They were operated in such a fashion as to warm the air over the landing strip by a few degrees. A few degrees is sometimes enough to cause a sufficient lifting of the ceiling to allow airplanes to land.

One of the chief difficulties with FIDO was the expense involved. The burners have to continue to operate or else the fog reforms or moves over the runway and closes down the field again. In war, expense assumes a secondary place in the scheme of things. But in peacetime, cost became a more decisive factor. After the war, FIDO went out of operation.

Then in the early sixties, interest in the FIDO scheme developed again. Scientists working for the U. S. Air Force began research to see if you could use surplus jet engines lining the runway to heat and mix the air. Some success was reported. French scientists also began a program of study leading to field tests of a similar scheme.

The results of all these investigations support the view that, given sufficient heat, the fog over landing strips can be cleared away, providing the winds are light. From there it becomes a question of, "Is it worth the price?" So far, no one has answered this question in the affirmative. For this reason, no airports in the United States, and none elsewhere, for that matter, yet are equipped to dissipate warm fog on a regular basis. As a result, it sometimes happens that airplanes headed for fog-bound Boston, for example, are forced to land at Hartford instead.

In the last chapter, we mentioned how carbon black was dispersed in clear air in an effort to produce cumulus clouds. Carbon black has also been employed in attempts to dissipate cumulus clouds. It was reasoned that by dusting a cloud with large numbers of black particles, the cloud would absorb more of the sun's rays. If this happened, the heating might lead to evaporation of the cloud droplets. A number of experiments was carried out by U. S. Navy and Air Force scientists in 1958 and 1959. Although there was some evidence that carbon black might cause some clouds to dissipate, it was not possible to reach positive conclusions. Definitive experiments to settle the issue one way or another have never been performed.

It is easy to be fooled when dealing with the dissipation of small cumulus clouds. On some days the sky is dotted with them for a good many hours. Every time you look up you see them there. But have you ever looked at one

single cloud for as long as ten or fifteen minutes? Some pleasant day when small cumuli are plentiful, lie on the grass and concentrate your attention on one of the many clouds. You will find that the cloud will disappear before your eyes in no more than about ten minutes.

Most small cumuli last for five to fifteen minutes depending on their size and the properties of the atmosphere. When the sky is cluttered with them, the total number of clouds may change slowly. As some clouds dissipate, others develop. As a result, it appears that the state of the sky is hardly changing at all. But each of the clouds changes fairly rapidly. Any experiment aimed at dissipating small cumulus must take these facts into account.

SUPERCOOLED CLOUDS

The most conspicuous examples of our ability to change the character of clouds are found with supercooled stratus and fog. We mentioned earlier that, in nature, when ice crystals enter such clouds, the water droplets evaporate and the ice crystals grow. In 1946, Vincent J. Schaefer, who was working as an assistant to the great scientist Irving Langmuir, took the first crucial steps demonstrating that it was possible to give nature a push once in a while.

Schaefer had made several trips to the top of Mount Washington in New Hampshire in the winter of 1943. He had been impressed by the degree to which everything, including buildings and instruments, was covered with ice. It was apparent that supercooled water droplets, driven by the winds, froze as they struck solid obstructions. In 1944, Langmuir and Schaefer, working at the General Electric Research Laboratory, took on the job of studying aircraft icing, that is, the accumulation of ice on airplanes flying through supercooled clouds. The Air Force was seriously concerned with this problem and it fascinated the scientists.

The interest in aircraft icing took Langmuir and Schaefer deeper and deeper into the study of all properties of clouds. Schaefer began to perform laboratory experiments on the behavior of water droplets. He supercooled them on clean

polystyrene and other surfaces to temperatures as low as −20° C. The question of the possible effects of the surfaces he was using always troubled him. This led to experiments with artificially produced clouds in a home freezing unit of the kind used to store frozen food. One imagines that it was a General Electric product.

In order to see the droplets in the box, Schaefer lined it with black velvet and shined a beam of light into the cold, black box. He then breathed into it. The moisture from his breath condensed and formed a grayish mass of water droplets. The temperature was −23° C, and the cloud of water droplets was supercooled, just as often happens in the atmosphere. Schaefer tried to produce ice crystals by dusting the cloud with various substances, but he didn't have much success. When a crystal did appear, it sparkled in the beam of light. The flat crystal face reflected the light much as a tiny, fluttering mirror might do.

One day in July of 1946, Schaefer decided he wanted to cool the box to temperatures lower than the refrigerating unit could handle. He figured this could be done by putting a large piece of Dry Ice in the chamber, for Dry Ice has a temperature of about −70° C. It produced cooling, and much, much more.

When the Dry Ice was put in the box, a countless profusion of ice crystals suddenly appeared. Schaefer had discovered an effective means to nucleate supercooled clouds. This was a classical case of serendipity, as Langmuir was later to note in his conversations. A competent investigator, engaged in the solution of one problem, made a fortunate discovery which became a key to the solution of many other problems.

Following the publication of Schaefer's work in 1946, it came to the attention of the scientific world that some years earlier someone else had used Dry Ice in attempts to modify clouds. August W. Veraart had seeded clouds in the Netherlands with Dry Ice in the summer and fall of 1930. He died in 1932, a year before Tor Bergeron proposed the theory of precipitation, forming the basis for understanding how Dry Ice leads to the modification of supercooled clouds.

Veraart deserves credit for having the insight to use Dry Ice, but Schaefer deserves even more. He discovered the use of Dry Ice independently, and by a series of related laboratory and field measurements was then able to demonstrate its effectiveness. Furthermore, Schaefer and Langmuir succeeded in putting the experimental work in its proper theoretical framework.

Schaefer found that if you produced a cloud of supercooled droplets in a deep-freeze box, even small fragments of Dry Ice caused enormous numbers of ice crystals. He showed that an ordinary sewing needle and other objects, when they were first cooled below about −40° C and then introduced into the box, would have the same effect. Thus it was concluded that Dry Ice produces crystals by cooling the air to below −40° C. At these temperatures the crystals can form directly from water vapor. Once some crystals are present, they grow rapidly at the expense of the supercooled droplets.

The experiments in the laboratory were complete successes. In the controlled atmosphere of the cold box, supercooled clouds were modified as ice crystals were created and fell to the floor of the box. Nature had been duplicated in miniature, or so it appeared. The next crucial step was to go out in the free atmosphere and experiment with supercooled clouds produced by rising currents of air.

The first test was made on November 13, 1946. Schaefer rented an airplane at the Schenectady Airport and he and the pilot went in search of a supercooled cloud. One was found over Pittsfield, Massachusetts, about fifty miles east of Schenectady. It extended to an altitude of 14,000 feet and had a temperature of −20° C. As the airplane flew through the cloud, Schaefer seeded it with three pounds of Dry Ice. He did this by opening the window and allowing the suction in the slipstream to pull out the particles of Dry Ice.

The airplane then swung around so Schaefer could see if there were any results. And results there most certainly were. Billions of crystals glistened in the cloud. It had been transformed into an ice crystal cloud. The experiment had worked just as it had in the deep-freeze box. When he

looked under the cloud, Schaefer saw a curtain of crystals snowing from the cloud to levels 2,000 to 3,000 feet below it. Again the cold box experiment was duplicated.

In his notebook, Schaefer reported, "Needless to say, we were quite excited." The thrill of such an occasion can never be adequately described. The joy of discovery, the pleasure of creating a new idea, the satisfaction of seeing a new conception verified are the real compensations of science.

When the airplane returned to the airport, Langmuir was waiting. From the control tower of the General Electric Laboratories he had watched the experiment and listened on the radio. He saw the fall of crystals following the seeding and was convinced clouds could be modified. In subsequent months, more successful flight experiments were made during which the tops of supercooled stratus clouds were seeded with Dry Ice.

The potential importance of cloud seeding did not escape Langmuir and his colleagues. In 1947, Project Cirrus was established at General Electric. In the course of the following years a great many theoretical, laboratory and field experiments were conducted. We shall come back to some of them in later parts of this book.

In 1946, Bernard Vonnegut joined the team of Langmuir and Schaefer. For the next five years or so, this triumvirate made the major contributions to the growth of knowledge and interest in cloud and weather modification.

The effectiveness of Dry Ice for producing ice nuclei was well established in short order. Vonnegut speculated that other substances might also convert supercooled clouds to ice crystals. He reasoned that another substance having the same crystal properties as ice might do the trick. He consulted tables giving the structure of over a thousand crystals. Three substances appeared to have possibilities. They were lead iodide, antimony and silver iodide. In the first experiments, samples of these substances were dropped into supercooled clouds in Schaefer's cold box. Relatively few crystals were produced, but not so few as to discourage further investigation. Vonnegut considered other means of seeding the clouds. He introduced tiny

silver particles into the supercooled cloud by drawing an electric spark from a piece of silver. Many ice crystals resulted and inspired the next step.

Vonnegut decided to produce a smoke of silver iodide particles by burning the substance. The resulting smoke consisted of vast numbers of tiny silver iodide crystals. When samples were blown into the supercooled cloud, the results were immediate and spectacular. The cloud was rapidly converted to ice crystals. The experiment clearly demonstrated that silver iodide smoke could effectively nucleate a supercooled cloud.

After his initial discovery of the efficacy of silver iodide for cloud nucleation, Vonnegut sought a technique for doing this on a practical basis. Several schemes finally evolved. If charcoal was impregnated with silver iodide and burned, great numbers of nuclei were produced. The same thing happened when the silver iodide was dissolved in a substance such as acetone and injected into a hot flame. By these methods, a single gram of silver iodide produced more than 10^{12} nuclei when put into effect at a temperature of about $-10°$ C. The lower the temperature, the greater the number of nuclei.

In 1948, supercooled clouds were seeded successfully with a special silver iodide generator, designed by Vonnegut, installed in an airplane. The results were similar to those found with Dry Ice. Ice crystals produced in a supercooled cloud grew and fell from the cloud, causing it to dissipate.

The early tests showed that you could "cut a hole" in a supercooled cloud. In some of them, the ground could be seen through the hole formed after the crystals fell out. Supercooled fogs could be cleared to a certain extent by means of ice nuclei seeding. These discoveries offered a valuable service to the air services operating in regions where supercooled, low clouds were common. But acceptance of the results of Project Cirrus was slow.

During the years 1951 to 1954, a large number of experiments involving the seeding of supercooled clouds was conducted by a group of U. S. Signal Corps scientists under the leadership of Hans J. Aufm Kampe and Hel-

mut K. Weickmann. The results confirmed and extended the earlier work. But still no practical use was made of the ideas.

United Air Lines, which has long been at the forefront in the application of new techniques for improving commercial aviation service, became interested in the problem in 1960. They planned to test ice nuclei seeding in Salt Lake City during the winter of 1962, but no supercooled fogs developed. The following winter, United contracted to have fog seeding conducted at Salt Lake City, Utah, and Medford, Oregon. At each airport, eight seeding operations were carried out on supercooled fog. They were largely successful. As a result, forty scheduled airline flights operated that otherwise would have been canceled or overflown the airport.

During the winter of 1964, United was joined by five other airlines operating in the Northwest and the number of airports at which seeding was done was increased to eight. The technique involved flying just over the top of supercooled fog and dispersing crushed Dry Ice from a small single-engine airplane. Quantities of Dry Ice used ranged from fifty to six hundred pounds, depending on the fog thickness, its temperature and its movement.

W. Boynton Beckwith, chief meteorologist at United Air Lines, reporting on their seeding activities, noted that "better than 80 per cent success was attained." Approximately two hundred flights were carried out which would have been canceled had it not been for the cloud seeding. He stated that "the direct benefits resulting from these programs outweigh the costs significantly. . . ." Of course, there also were many indirect benefits, such as many satisfied passengers. Only through experience can you appreciate the annoyance of flying in a circle for an hour waiting to land at a fogged-in airport and then finally having to land at some other airport.

In the fog-clearing work done through 1965, fairly simple, and relatively crude equipment was used. Little so-called engineering data existed in the scientific literature before that time. By engineering data we mean specific information on quantities of Dry Ice, pellet sizes and pat-

terns of dispersal to be used for clearing clouds of particular types and temperatures.

In 1966, William W. Vickers and James F. Church, working for the U. S. Air Force, published an article dealing with this subject. They had set out to determine optimal cloud seeding techniques. In the course of their work over a three-year period, they had also developed a Dry Ice seeding machine called the Cloudbuster. (See Plates 9 and 10.) It puts out known quantities at known pellet sizes. For example, it can dispense Dry Ice particles one centimeter on a side at a rate of 10,000 per minute. In the 1966 article, Vickers and Church recommended that the seeding airplane fly along paths across the wind and seed between four and nine pounds of Dry Ice per nautical mile of flight. Their article represents the type of engineering research much needed in this phase of weather modification.

In certain other parts of the world, France, for example, and the Soviet Union in particular, there has been great interest in this same problem.

At Orly Airport in Paris, French engineers have installed a network of sixty devices for releasing propane gas. The expansion of the gas results in pronounced cooling and the formation of ice crystals, which act to dissipate supercooled fog. The operation is almost completely automatic. When supercooled fogs occur, the control tower operator presses a button and sets the whole operation in motion. Wind velocity is measured and fed to a computer which determines which banks of propane gas seeders are operated. During the winter of 1967 propane was also used on a test basis at the airport in Medford, Oregon and was reported to have significantly improved flying weather in fifteen of twenty-five tests.

In Russia, supercooled clouds and fog are often a problem. As a consequence, there has been extensive research done on the use of ice nuclei. Among the leaders in this work have been V. Ya Nikandrov at the Main Geophysical Observatory in Leningrad.

In the late forties, Nikandrov and his colleagues were very active in the study of the efficacy of Dry Ice. Some

laboratory experiments apparently were conducted as early as 1946 or 1947, probably inspired by Schaefer's work. By 1957, Nikandrov had written a series of articles on the subject, including a detailed theoretical analysis of the use of Dry Ice for clearing supercooled fog. During the same period, a number of field experiments were carried out to develop engineering data for optimum cloud dissipation.

In 1958, E. K. Fedorov, the director of the Soviet Hydrometeorological Service, stated, "The problem of the dispersal of supercooled clouds can be considered solved in principle. At present, in the U.S.S.R. a distinct technology for opening airports in winter is being completed and introduced into practice. Successful dispersal is being accomplished over expanses of 10 to 15 kilometers."

As part of their weather modification program, Soviet scientists tried various schemes for producing Dry Ice pellets. Crushed Dry Ice is simple to use, but you need a convenient place to store large quantities. At any particular airport, weeks might go by without supercooled fog and then it may occur several days in a row. One technique for overcoming the carbon dioxide (CO_2) storage problem makes use of compressed liquid CO_2. When the nozzle of a tank is opened, CO_2 gas expands and forms flakes of Dry Ice. In a suitable chamber, the flakes can be caused to clump and form pellets.

Russian scientists have tested devices where Dry Ice pellets can be fired from the ground into fogs. They have used balloons to carry bags of Dry Ice into clouds. These schemes, if perfected, could make seeding possible on days when even the birds stay on the ground. The Soviets were among the first to use so-called pyrotechnic seeding devices. In 1958, they seeded clouds with tracer bullets impregnated with silver iodide. There is no record that this technique was given a special name. Perhaps it could be called the "cloud blaster" to go along with the Air Force's Cloudbuster.

According to a statement by Fedorov, it was planned that by the winter of 1964 there would be cloud seeding apparatus at twelve airports in the Soviet Union.

A Russian article in 1961 gives another example of how cloud dissipation can be of value. On February 15, 1961, supercooled fog covered the Crimean Astrophysical Observatory. This was not at all unusual in February, but on that particular day an unusual event was to occur, a total eclipse of the sun. The astrophysicists wanted to see it, and that could be done only if the clouds were cleared away.

Scientists from the Institute of Applied Geophysics near Moscow flew to the airport at Simferopol. They intended to try to keep the line between sun and observatory clear. Two planes were used. After some preliminary measurements of cloud thickness and temperature and wind velocity, they started seeding with Dry Ice pellets. The aim was to dissipate an area large enough so that the sky over the observatory would be clear for two hours. According to reports, the operation, though not a perfect success, was certainly worth the effort. About 70 to 75 per cent of the planned observations of the eclipse were carried out successfully.

There is no longer any question that, most of the time, ice nuclei seeding of supercooled fogs and low clouds will cause them to dissipate. In some cases, updrafts may produce new clouds faster than the old ones can be dissipated. In other instances, the clearing may close in a short time. But the frequency of successful dissipation makes the use of seeding of practical importance.

Nevertheless, there has been a great deal of foot dragging in putting cloud-dissipation techniques into practice. At this point, the job is largely an engineering one. Present efforts in the U. S. Air Force are going in the right direction, but they need to be enlarged and accelerated. Certainly it is only a matter of time before supercooled fogs will be cleared from all airports on a regular basis.

STIMULATING THE GROWTH OF CLOUDS

Since the early sixties, Dr. Joanne Simpson and her colleagues have carried out a series of investigations dem-

onstrating that certain convective clouds can be made to grow to greater altitudes by means of cloud seeding.

The vertical development of a cumuliform cloud having a particular diameter depends to an important degree on the temperature and moisture of the atmosphere. In some situations, there are "stable layers" at altitudes between 20,000 and 30,000 feet which inhibit further cloud growth. The stable layers are regions where the temperature increases or decreases gradually, with height. The rising cloud air, when passing through such a layer, is subjected to a downward force. Sometimes, depending on the strength of the cloud updraft and the stability of the layer, the cloud's growth is halted.

If a cloud, just barely stopped from further growth, is given some additional buoyancy by a raise in temperature of a degree or two, the buoyancy will produce an upward force allowing the cloud to penetrate the layer. Once this has happened, the cloud might grow rapidly for many thousands of feet. When large quantities of supercooled cloud water is rapidly frozen at temperatures near the $-8°$ C level, the released latent heat of fusion can produce additional warming of about 1 or 2° C. The idea that additional cloud buoyancy could be obtained by means of large doses of artificial ice nuclei was first tried in 1947 in Australia by two atmospheric scientists, Patrick Squires and Eric B. Kraus.* The same notion was proposed independently by Irving Langmuir at about the same time. Little was done to make a systematic test of this idea until 1963, when Dr. Simpson became interested in it.

She developed a mathematical model of a convective cloud and then calculated what clouds of particular diameters would do if they were left alone and if they were seeded. In her later experiments, she identified suitable clouds, and following a randomized scheme for selection, seeded somewhat more than half of them. Silver iodide was used as the seeding agent. At the conclusion of the

* Patrick Squires is now at the University of Nevada and Eric B. Kraus is at the University of Miami.

tests, the vertical extents of all clouds were compared with calculations of the expected extents. It was found that in accordance with theoretical expectations, the ice nuclei seeding caused the clouds to grow an average of about 5,000 feet. Somewhat similar studies giving similar results have been carried out by other investigators, notably Larry G. Davis at Pennsylvania State University.

It has been suggested, quite reasonably, that those clouds whose growths were stimulated by the ice nuclei produced more precipitation than would have been the case had they been left alone. Difficulties in measuring rainfall from individual convective clouds has prevented, so far, a satisfactory test of this suggestion. As will be seen in the next chapter, the evaluation of techniques for rainmaking is not as easy as it may appear.

8

RAIN ON TAP?

We have seen that the seeding of supercooled clouds caused some precipitation to reach the ground, but the questions of how much, when and where still remain to be answered. Most of the effort of weather modifiers over the last two decades has been concerned with finding ways to produce significant increases in rainfall. This subject has received a great deal of attention from laymen as well as scientists. The news sources have had numerous articles on rainmaking by means of cloud seeding. Many of them have been optimistic, leading the reader to believe that practical rainmaking was already a reality. Other articles have been wrapped in tones of pessimism. Surely the public has been, and continues to be, confused on where we stand.

Shortly after Vincent J. Schaefer performed his successful experiments on cloud seeding, it appeared that a technique for increasing precipitation was just around the proverbial corner. Some snow was seen to fall from the thin supercooled clouds infected with ice crystals. Of course, the quantities of snow reaching the ground were small, but this was to be expected from clouds just a few hundred meters thick. It was reasoned that if thicker clouds were seeded with Dry Ice or silver iodide, substantial amounts would precipitate.

By the 1950s, a number of commercial cloud seeding companies had been formed. They were able to convince ranchers, directors of power companies, city officials and others that they could bring more rain or snow by means of cloud seeding. Some of the early seeding companies are still operating today, others have gone out of business. Some of the latter have been replaced by new ones. For the most part, reports of the commercial cloud seeders generally indicate successful operations. Although the

commercial operators published few articles in the scientific literature until the early 1960s, they claimed that rain and snow had been increased by economically important amounts.

Until fairly recent years, that is, the middle sixties, the scientific community in general was skeptical about claims that precipitation had been increased. As we shall see, there were various reasons for the skepticism.

VARIABLE NATURE OF RAIN AND SNOW

Everyone is familiar with the variable nature of rainfall. It changes from one place to another by astounding degrees. This is particularly true in the case of showers and thunderstorms. Such storms may be only a few miles in diameter, and a torrential downpour may occur in one part of town while the sun is shining a few miles away. This type of storm behavior gives headaches to the weather forecasters. You probably have heard the forecast "scattered thunderstorms in the afternoon." The weatherman does not mean that every part of town will get wet at various times of the day. He means that thunderstorms will be distributed over the area—one here, one there and in most places none at all.

The variations in duration and time of occurrence of rain and snow are even greater than the variations in space. Again, they are most striking in the event of thunderstorms. Sometimes they start and stop in matters of minutes. One day, showers bring barely a sprinkle; other days, an inch or two may fall in an hour. The quantities of precipitation change from week to week, month to month, year to year, even century to century. When rainfall is far below normal, and this occurs someplace almost every year, drought threatens. If the situation continues, the threat becomes a reality, as we saw in Chapter 1.

It is in order here to say something about so-called "normal" weather. You sometimes hear radio and television weathermen say such things as, "The normal rainfall for this month is 3.40 inches." In this context, the

word "normal" refers to the average taken over the thirty-year period 1921 to 1950. Normal rainfall for the month of August at the University of Arizona in Tucson, Arizona, for example, amounts to 2.11 inches. In this instance, the weather records go back to the year 1895. Over the seventy-four years of record, extending through 1968, average August rainfall in Tucson has been 2.09 inches. In fact, the actual monthly quantities have ranged from a low of 0.08 inches in August 1924 to a high of 5.61 inches in August 1935. The so-called "normal" of precisely 2.11 inches has *never* occurred!

The reason for dwelling on the variability of rainfall and snowfall is to emphasize the background against which rainmaking experiments must be evaluated. There have been cloud seeding experiments where the rain that fell during one period was compared with the "normal" rainfall. This approach is virtually hopeless unless the seeding is capable of bringing about rainfall increases considered to be unreasonably large.

For example, suppose clouds over Tucson were seeded in August of 1975 and 2.50 inches of rain fell that month. This would represent an amount about 20 per cent above normal. Could you justifiably claim that the cloud seeding had caused an increase of 20 per cent? Of course not! The records show that of the seventy-four Augusts since 1895, 2.5 inches or more fell on twenty-six months. Thus you would expect this amount about once out of every three years without seeding. This likelihood is so high that you could not reasonably rule out natural causes as the explanation for the 20 per cent difference.

If the quantity of rainfall over a given area could be accurately forecast, the problems of variation could be overcome. If it were possible to predict that the precipitation would amount to precisely 0.20 inches on a particular day, for example, the evaluation of a rainmaking scheme would be relatively easy. Unfortunately, quantitative forecasts cannot be made with sufficient accuracy, not yet anyway. Someday, in the decades to come, when we know more about the atmosphere and have the necessary observations and computing facilities, it might be

possible. Today we can rely on forecasts to give acceptable information on whether or not it will rain or snow and, in some cases, even an estimate of the quantities, but not with the reliability needed to test a rainmaking procedure.

STATISTICS FOR BETTER OR WORSE

Since we cannot use forecasts and are faced with terrible problems of rainfall variability, what is left? Fortunately, the powerful techniques of statistics are left. They allow us to tackle the evaluation of rainmaking experiments in a quantitative way.

For many people, and not only laymen, the field of statistics is a field to avoid. Surprisingly, this attitude is widespread among a large segment of the scientific community. Apparently, lack of understanding of the principles of statistics has prevented a great many people from appreciating their usefulness in a large variety of problems.* That is not to say that statistics are necessary in the treatment of all scientific investigations, or even most of them. Certainly the major share of great conceptions in science did not require a knowledge of the laws of statistics. Nevertheless, there are a large number of questions for which reliable answers can only be obtained by the use of what are called "tests of inferences." The types of questions falling into this category are those seeking to find small differences among highly varying and unpredictable quantities. Many examples could be cited.

How can one test the worth of a new fertilizer? Since its effects on corn yields cannot be accurately predicted, the fertilizer has to be evaluated by field experiments. It is known that the yield of any particular field will vary from one year to the next, depending on such factors as the weather and soil conditions. Over the years, a satis-

* See Warren Weaver, *Lady Luck: The Theory of Probability* (New York: Doubleday Anchor Science Study Series S30, 1963).

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factory test procedure has been devised. Two similar fields are planted with the same species, in the same way and at the same time. Only one of them is selected at random for treatment with the fertilizer. At the end of the growing season, the yields of the two fields are compared. By means of statistical tests, the probability that the observed difference in yields came about by chance can be calculated. If the chance of natural occurrence of the difference is very small, it may be concluded that the fertilizer was effective.

A look at the facts makes it clear that statistics have to be employed in order to obtain quantitative answers to the question "Can cloud seeding increase precipitation at the ground and by how much?" A discussion of design of cloud seeding experiments and statistical tests to be employed might take the reader off the main track of this book. He is referred to the additional reading material listed near the end of the book. However, a few essential points should be made here.

In order to make valid statistical tests, it is essential that the experiment be properly designed at the outset. There should be built-in controls to minimize the amount of bias for or against positive results. One satisfactory procedure is to use two geographical areas, one of which is never seeded and serves as a control. Another area having similar climatological properties and often called the "target area" is seeded on a random basis. During periods when conditions appear to be appropriate for seeding, a decision is made whether or not to seed according to a scheme akin to flipping a coin. Heads you seed, tails you don't. Comparisons are made of the quantities of rainfall over the control area to the quantities over the target area on seeded and not-seeded days.

Many commercial cloud seeders have made use of target and control areas and have seeded the former whenever suitable clouds were present. Usually the target area has been the property of the client, perhaps a large ranch, a group of farms or the watershed of a power company. In these operations, the customer was paying the costs in the hopes of getting more rain or snow. As a result, the

target was seeded at almost every opportunity. Because such procedures do not generally have suitable provisions for avoiding bias on the part of the cloud seeder, statistical analyses of data from these projects are usually clouded with some uncertainties.

Since 1946, many cloud seeding operations have been carried out, the preponderance by commercial cloud seeders. Some purely experimental tests have been performed by university and government organizations. An examination of the results shows why even the experts disagree about the effects of cloud seeding on rainfall.

SEEDING FROM AIRPLANES AND GROUND-BASED GENERATORS

Let us first consider those experiments which have involved seeding clouds from airplanes. A small number of tests have been conducted with "warm" clouds. They were seeded with sprays of water droplets or salt particles in order to stimulate the coalescence process. The evidence indicates that in some cases precipitation was started, but measurements of rainfall at the ground are almost nonexistent. In the tropical regions of the world, where the coalescence process appears to predominate, this type of seeding may someday be found to be practical, but at present this point has not yet been established.

Most attempts to increase precipitation have made use of ice nuclei. Airborne silver iodide generators of various kinds have been employed. (See Plate 11.) In some projects, particularly in the Soviet Union, Dry Ice has been used extensively. There is no doubt that ice nuclei seeding of supercooled clouds is capable of starting the growth of ice crystals which will fall towards the ground. This does not necessarily mean, however, that cloud seeding can increase precipitation by a significant amount.

Russian meteorologists have reported precipitation increases of 10 to 15 per cent. The information appearing in the literature makes it difficult to decide if their claims of statistical significance can be accepted.

In Canada, large storm systems in the summer were

seeded with silver iodide over a four-year period. No evidence of rainfall increase was reported.

In Israel, winter storms were seeded according to a carefully designed statistical procedure. Airborne silver iodide generators were employed. After four and a half years of tests, it was reported that on seeded periods there was 15 per cent more rainfall. Statistical tests indicated that the chances of such results without seeding were only about one in ten. Hence it appeared that the rainfall increases came about because of the cloud seeding.

Positive effects have been reported in Japan. In Australia, some tests have indicated silver iodide increased precipitation at the ground. Others indicated decreases in precipitation.

Airborne silver iodide seeding of convective clouds has produced mixed results. Seven summers of testing clouds over the Santa Catalina Mountains in southeastern Arizona failed to demonstrate an increase of rainfall. There actually was less rain on seeded days, but the results cannot be regarded as "statistically significant." A long series of experiments in Missouri by Roscoe R. Braham, Jr., and his colleagues at the University of Chicago have yielded puzzling results. Overall, there was less rainfall on seeded areas and for a distance more than 100 miles downwind.

An interesting series of experiments on individual convective clouds was carried out in the middle sixties by Australian scientists. The results suggest that the effects of silver iodide seeding on rainfall depends on cloud-top temperatures. They have reported that more rainfall could be produced when cloud-top temperatures were below about −10° C.

We have cited these various results to illustrate the range of successes and failures presented in the scientific literature. Some projects inspire optimism; some, pessimism; others, uncertainty. It surely cannot be said that rainmaking has reached the engineering stage. On the basis of the evidence, one usually cannot specify beforehand whether a given quantity of silver iodide will

increase or decrease precipitation at the ground or possibly have no effect at all.

In order to seed with Dry Ice, it is necessary to employ airplanes or perhaps balloons or rockets to deliver the material into the cloud. When silver iodide is used as the seeding agent, clouds may sometimes be seeded from ground stations. Because of the relatively low cost of operation and because of their convenience, ground-based generators have been used extensively in rain and snow augmentation projects. (See Plate 12.) The ice nuclei produced by standard silver iodide generators are quite tiny—0.001 to 0.1 micron in diameter. They are carried along with the air. If the generators are properly located, rising currents of air may carry the nuclei into the supercooled regions of the clouds. Note that if the generators are not carefully positioned, the nuclei may never reach the appropriate levels in the clouds over the target area.

EVALUATIONS OF RESULTS

As already noted, commercial operators were very active during the late forties and early fifties, particularly in the western part of the United States. Reports in the public press and debates at scientific meetings aroused the curiosity of the public, the Congress and the federal government.

In 1953, President Dwight D. Eisenhower, at the instigation of Congress, appointed a special study group called the Advisory Committee on Weather Control. The late Howard T. Orville, who had been the chief of the Navy Weather Service, was named chairman. Herbert C. S. Thom was appointed chief climatologist. The purpose of the committee was to investigate the status of weather modification and report to the President.

It was not intended that the committee carry out field experiments, but rather that its meteorologists and statisticians analyze the results collected by others. Most of the available data were those in the files of the commercial cloud seeders. They were turned over to Thom and his associates, who did the best they could with them, while

1. Flooding of downtown Raymondville, Texas, caused by rainfall from Hurricane Beulah in September 1967. *Environmental Science Service Administration Photo.*

2. Aftermath of a tornado in Topeka, Kansas, on June 8, 1966. *Courtesy R. E. Townsend.*

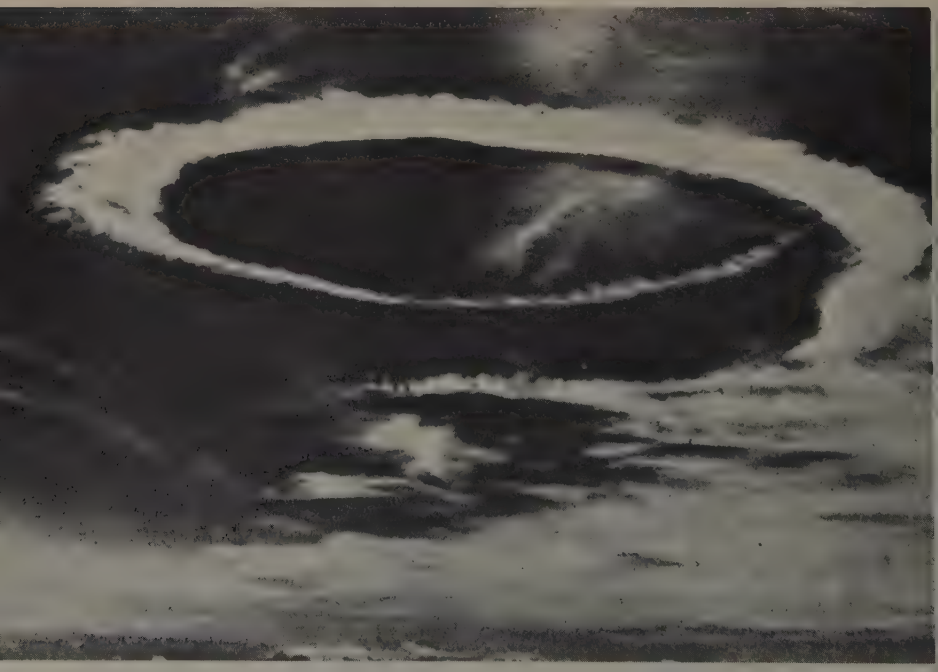
3. Hail and rain damage to Ed H. Horman's cornfield near Otley, Iowa. *Photograph by United States Department of Agriculture.*

4. Droughts lead to blowing sand and soil and desolation. *ESSA Photo.*

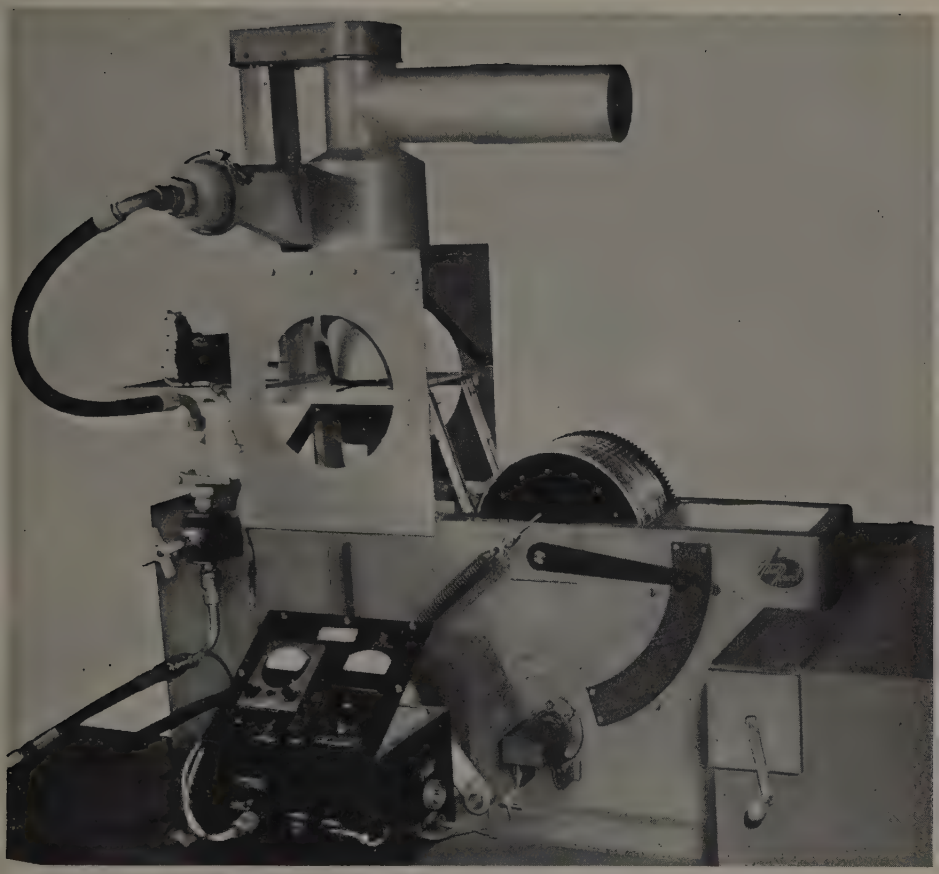
5. A snowstorm immobilizes the nation's capital. *ESSA Photo.*

6. Changing the microclimate of a lemon orchard. The heaters warm the air and trees on cold nights and reduce the amount of frost damage.

7. Meteotron in France. It consists of 100 fuel oil burners over an area 100 by 100 meters. It consumes one ton of fuel oil per minute. *Courtesy H. and J. Dessens.*



8. Clouds at an altitude of 27,000 ft. produced by dropping Dry Ice from an airplane. *Courtesy of General Electric Company.*

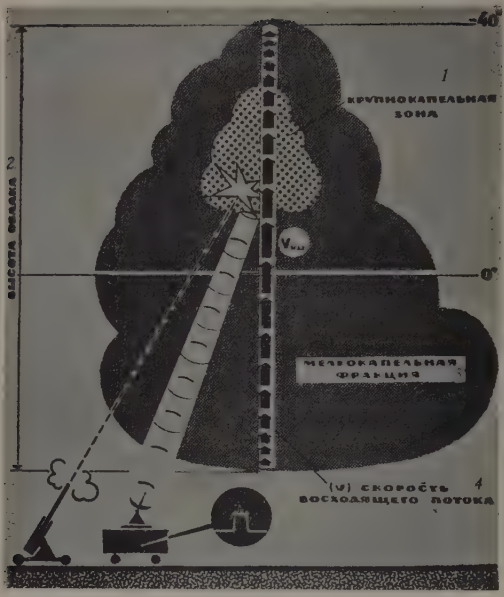


9. Prototype Cloudbuster Dry Ice seeding apparatus developed by U.S. Air Force. Liquid carbon dioxide is converted to CO_2 pellets and dispersed from airplane. *Courtesy Lt. Col. J. F. Church, Air Force Cambridge Research Labs.*

10. By means of Dry Ice seeding a hole is "cut" in a deck of altostratus clouds 600 ft. thick. Seeding was done with Cloudbuster device shown in Plate 9. *Courtesy Lt. Col. J. F. Church, Air Force Cambridge Research Labs.*

11. High-output airborne silver iodide generator manufactured by Meteorological Research, Inc. The generator is mounted under the wing of a light airplane. The upper cylindrical container contains a silver-iodide-in-acetone solution. The highly inflammable liquid is sprayed into the burning chamber hanging at the bottom. *Courtesy of Meteorological Research, Inc.*

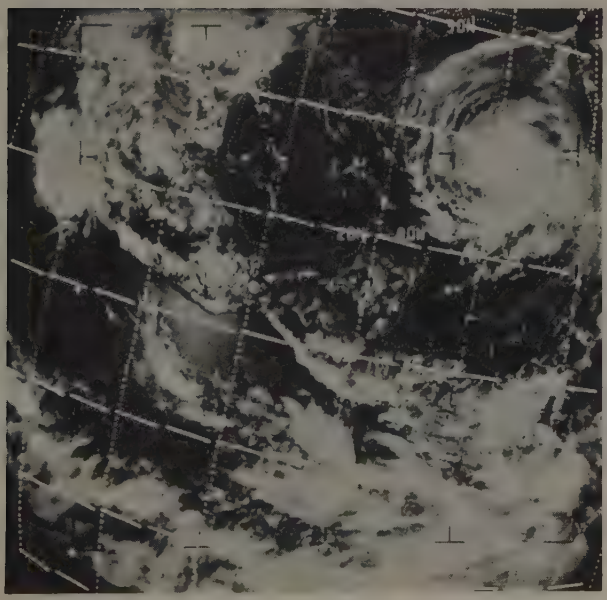
12. Ground-based silver iodide generator. The compressed air in the left-hand tank forces a silver iodide solution into the burner on the right. A smoke of silver iodide crystals comes out the top of the chimney. *Courtesy H. and J. Dessens.*



13. Sketch of hail-producing cloud and technique for hail suppression developed in Soviet Union by G. K. Sulakvelidze and associates. Translations of the Russian labels are as follows: 1) Large-droplet zone; 2) Height of cloud; 3) Small-droplet fraction; 4) Velocity of updraft. The indicated temperatures are in degrees Celsius.

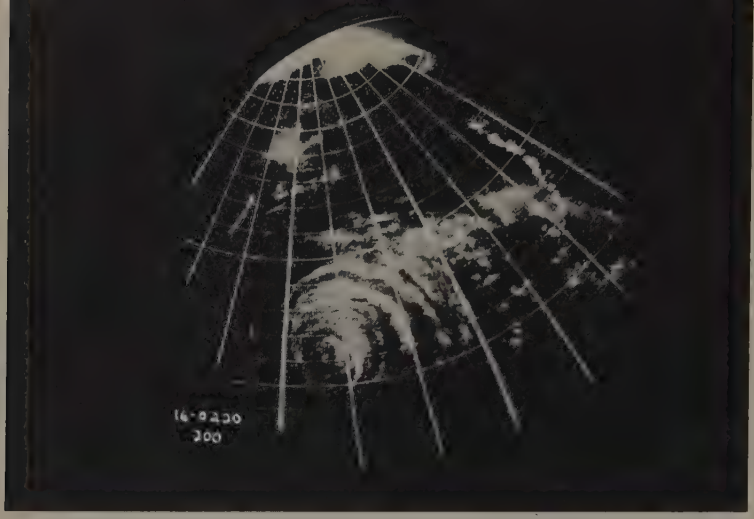
14. Russian artillery piece firing silver iodide charged explosive into thunderstorm for the purpose of suppressing growth of damaging hailstones.

15. Spectacular lightning display in Arizona photographed by long-time exposure. *Courtesy L. E. Salanave.*

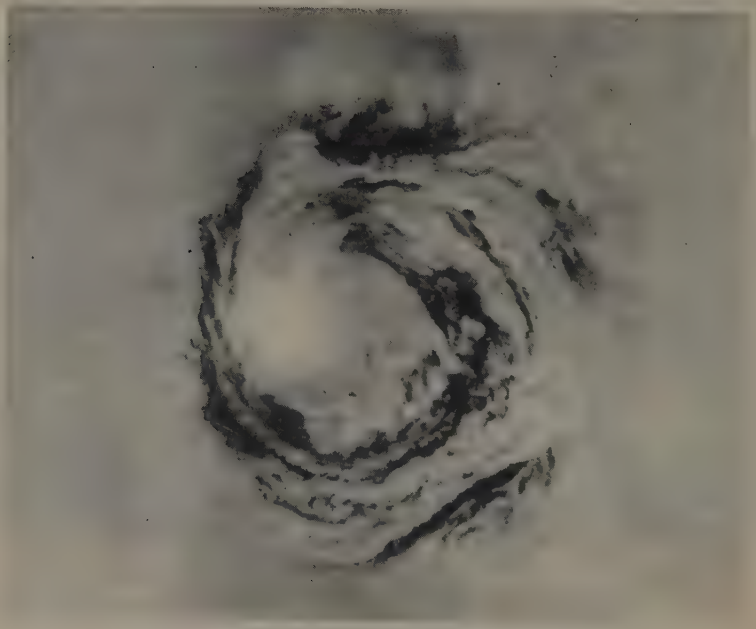


16. ESSA 3 photograph of Hurricane Inez west of Florida on October 5, 1966. The Gulf of Mexico, the western Caribbean, Mexico and Central America are visible. *ESSA Photo.*

17. Firing of anti-hail rocket to altitude of about 6000 ft. Rockets are manufactured by Societa-Italiana Prodotti Esplodenti in Milan which kindly supplied these photographs.



18. Radarscope showing hurricane centered at distance 135 miles almost due south of Orlando, Florida, the site of the radar set. *ESSA Photo.*



19. The eye of Hurricane Beulah, photographed by an airplane of the 58th Weather Reconnaissance Squadron of the U.S. Air Force. The aircraft was flying at an altitude above 60,000 ft. approximately 150 miles off Tampico, Mexico, late on the day of September 19, 1967. *Courtesy U.S.A.F. Air Weather Service.*

at the same time recognizing the limitations of these data. In making their studies, they selected those projects where the rain and snow observations could be reasonably checked. The evaluations made use of the target-control area technique mentioned earlier.

In 1957, the committee issued its final report,* containing the following conclusions:

> On the basis of its statistical evaluation of wintertime cloud seeding using silver iodide as the seeding agent, the committee concluded that:
>
> (1) The statistical procedures employed indicated that the seeding of winter-type storm clouds in mountainous areas in the western United States produced an average increase in precipitation of 10 to 15 per cent from seeded storms, with heavy odds that this increase was not the result of natural variations in the amount of rainfall.
>
> (2) In nonmountainous areas, the same statistical procedures did not detect any increase in precipitation that could be attributed to cloud seeding. This does not mean that effects may not have been produced. The greater variability of rainfall patterns in nonmountainous areas made the techniques less sensitive for picking up small changes which might have occurred there than when applied to the mountainous regions.
>
> (3) No evidence was found in the evaluation of any project which was intended to increase precipitation that cloud seeding had produced a detectable negative effect on precipitation.

The report of the advisory committee was greeted with mixed reactions. Some scientists regarded it as strong evidence that, at least in some cases, precipitation could be increased by means of silver iodide seeding. On the other hand, the work of the committee was severely criticized by a number of prominent statisticians. Among the outspoken critics were K. Alexander Brownlee of the University of Chicago and Jerzy Neyman of the Univer-

* *Final Report of the Advisory Committee on Weather Control,* Volumes I and II (Washington: U. S. Government Printing Office, 1957).

sity of California at Berkeley. The gist of the criticisms was that the conclusions were based on data collected in an improper manner. It was argued that the lack of experimental controls made the observations unreliable.

Because the conclusions were based on statistical analysis, the views of expert statisticians could not be ignored. In fact, the criticisms of the advisory committee report were more or less shared by a major part of the scientific community. It was the general feeling that while the studies of the committee represented evidence that seeding might increase rain or snow in certain situations, it was certainly not yet proved.

In 1957, the opinion was expressed by members of the advisory committee and by its critics that carefully designed and controlled cloud seeding projects would be needed to settle the dispute. Several such projects were begun at that time. With a certain degree of hope, a cloud seeding experiment was planned in Santa Barbara County, California. It was a joint effort of a number of agencies. Of particular interest was the fact that among the participants were Jerzy Neyman, the statistician, and a commercial company, North American Weather Consultants. This company, under the presidency of Robert D. Elliott, has long been one of the leading private organizations engaged in weather modification work.

The aim of the project was to seed winter storms over California, the kind of storm the advisory committee found amenable to cloud seeding. During the winter of 1957, everything went reasonably well and it appeared that the ground-based silver iodide seeding might have increased the precipitation. With a certain degree of optimism, virtually everyone interested in the problem was looking forward to a continuation of identical tests for several more winters. Unfortunately, this was not to be.

The seemingly positive results became known to people in counties neighboring Santa Barbara. In particular, community leaders in adjacent Ventura County decided to engage in silver iodide seeding during the winter of 1958 so they might also get more rain and snow. On many occasions it was not possible to rule out the possi-

bility that seeding nuclei from Ventura were infecting the clouds over Santa Barbara. As a result, the scientific value of the Santa Barbara project was greatly diminished.

During the following winter, the experimental design of the research project was changed to include both counties. As a consequence, after three years, the experimenters were left with one year's data on three separate experiments. Their aim had been to get three or four years' data on one experiment. The net result was that it was impossible to get a satisfactory answer to the question "Does silver iodide seeding increase precipitation?"

Earlier, we mentioned a program of airborne randomized seeding of convective clouds conducted over a period of seven summers in southeastern Arizona. This work, started in 1957, was under the direction of the author at the University of Arizona. It failed to show that rainfall at the ground could be increased.

A program of airborne seeding over the Snowy Mountains of Australia was started in 1955 by E. G. Bowen and his associates at the Commonwealth Scientific and Industrial Research Organization in Sydney. After five years, it was concluded that although there was some indication of increased precipitation it could not be proven. Several other projects in Australia gave mixed results.

Meanwhile, in various parts of the world, particularly in the United States, commercial cloud seeders continued to seed clouds for a variety of customers. Little information found its way into the scientific literature, but mimeographed reports to clients most often reported positive results. Generally, the reported increases were below 20 per cent, but some were much higher.

When considered against the background of other scientific activity in the United States, research in weather modification during the period 1957 to 1963 was modest indeed. Total federal expenditures were less than three million dollars per year. For many years, Earl G. Droessler, who was the head of the weather modification effort at the National Science Foundation, urged enlargement of the research effort. His cries went largely unheard both inside and outside the Foundation.

In the early sixties, the Bureau of Reclamation became interested in rainmaking. They felt that since water was their business they should do what they could to put more of it behind the dams they built all over the West. As a consequence, the bureau went to Congress for funds to start a program in weather modification. They found receptive ears in the Senate committee chaired by Senator Clinton Anderson of New Mexico. He long had been and continues to be interested in the subject of water, particularly in the investigation of any and all ways to get more of it.

At about this time, the National Academy of Sciences, which had begun to become more aggressive in scientific affairs, became interested in this problem. In November 1963, its Committee on Atmospheric Sciences, headed by Thomas F. Malone, vice-president for research at Travelers Insurance Company, appointed a Panel on Weather and Climate Modification. The chairman of the panel was Gordon J. F. MacDonald of the University of California at Santa Barbara.

The panel held meetings with scientific and technical people at various places around the United States. After a series of such conferences, some of which discussed recent research in great detail, the panel issued a preliminary report in October 1964. Unfortunately, it was not clearly marked as "preliminary," "not for quotation," or in some such fashion as to indicate that it was not to be taken as the final word. As a consequence, it stirred up considerable controversy and criticism from scientists in universities, government and particularly private weather companies. The preliminary report was not only premature in the sense that a great deal of relevant information had still not been examined, but in some cases it drew generalizations not supported by the facts already on hand.

Commercial cloud seeders were critical of the panel for not having examined the results of their projects. They were prepared to admit that the data obtained in these projects were not ideal for scientific investigation. On the other hand, they felt that something could be learned.

James E. McDonald, who was added to the panel in 1965, agreed to make a careful review of the reports of a number of projects carried out by commercial cloud seeders. His background as a cloud physicist who was close to cloud seeding activities and who understood the statistical aspects of the problem made him well suited for the assignment. In a sense, McDonald repeated what had been done almost ten years earlier by Herbert Thom, who was chiefly responsible for the analysis of the President's advisory committee. McDonald took little for granted. He examined only those projects where the rainfall data were collected by agencies other than the cloud seeders. Tracking down the relevant information was a time-consuming, and, in some cases, frustrating occupation.

Most of the analyses involved comparison of rainfall over a target and a control area. In four projects in the mountains of the western United States, the runoff of rain and melted snow in target watersheds was compared with the runoff in control watersheds.

The panel released its final report in January 1966.* Its tone differed markedly from the earlier preliminary report. In particular, the sections dealing with rainmaking reflected the results of the new analyses.

The chief conclusions are summarized in Volume I (italics are those in the report):

> *1. There is increasing but still somewhat ambiguous statistical evidence that precipitation from some types of cloud and storm systems can be modestly increased or redistributed by seeding techniques. The implications are manifold and of immediate national concern.* The evidence is complex and, in part, contradictory. . . .
>
> (a) *Orographic storms.* Evaluations (by this panel) of 41 project-seasons of winter orographic cloud seeding by commercial operators in the western United

* *Weather and Climate Modification—Problems and Prospects.* Final Report of the Panel on Weather and Climate Modification, Volumes I and II, Publication No. 1350, National Academy of Sciences–National Research Council, Washington, 1966.

States support the earlier conclusion (by the Advisory Committee on Weather Control in 1957) that precipitation increases of the order of 10 percent apparently can result from ground-based silver iodide seeding of winter orographic storms. Similar but more variable and equivocal results have come from field research projects in many parts of the world. . . .

(b) *Cumulus clouds.* Experimental and operational evidence relating to the stimulation of cumulus precipitation remains highly confusing. The Panel's evaluations of 14 operational silver iodide seeding projects in the eastern United States, including *but not limited to* cumulus clouds, indicate variable rainfall increases averaging about 10 to 20 percent in the nominal target areas. A recent follow-on study made at the Panel's request suggests comparable increases up to 150 miles downwind of the targets. Project Whitetop, a randomized cumulus seeding experiment in Missouri, tentatively indicates about 5–10 percent increases in the nearby target area, and also decreases of about the same size (rainshadow effect) downwind from the target area. Final Whitetop conclusions are awaited with interest. . . .

(c) *Extratropical cyclones* (*nonorographic*). There is no clear evidence of success to date in stimulating precipitation from this type of storm in the United States; but little effort has been made except by commercial operators whose records make no distinction between cyclonic and other storm types. Reports from Russia, Israel, and Japan indicate increases of varying amounts due to both silver iodide and dry-ice seeding, while other results (Australia, Canada) show no apparent seeding effects. Reported Russian results show some evidence also of a downwind decrease (rainshadow) beyond the nominal target area.

The major problem in assessing seedability is the great natural variability of the principal precipitating cloud systems. . . . Furthermore, this variability leaves open the possibility that *decreases* in precipitation may sometimes result from seeding, a possibility that might well also be turned to useful purposes. It is likely that some clouds are not responsive to silver iodide seeding, e.g., those with an abundance of natural ice crystals and those that are warmer than 0°C throughout. . . .

The wording used in these conclusions may seem to be unnecessarily equivocal. But this was done purposely. The panel did not intend to say, and did not say, that it was proven beyond reasonable doubt that silver iodide seeding could increase rain or snow. It did state that there are reasons for believing that in certain circumstances it might be possible to increase precipitation by 10 to 20 per cent. The possibility that in other instances precipitation might be decreased was also recognized. Finally, it has been found that in still other cases seeding would probably have no detectable effects.

K. A. Brownlee, the statistician who had violently criticized the 1957 report of the Advisory Committee on Weather Control, was equally upset by the 1966 report by the academy panel. In a published review of its final report, he wrote a scathing attack on the validity of the statistical tests. Nevertheless, the attitudes among most atmospheric scientists had changed considerably. By the late sixties, there existed a greater feeling of optimism about weather modification than there was at the start of the decade.

If you are a farmer in Illinois, you might ask, "But what does all this mean to me? Can I get 10 per cent more rain on my corn if I seed during July and August?" On the basis of the results to date, the answer would have to be that maybe you could, maybe not. There is no satisfactory means of making more meaningful predictions, unless you know more about the character of the clouds during the period of interest. If you do decide to seed the clouds passing over your farm, however, you should recognize that you are taking a calculated risk. Insist that the seeding be carried out in such a way as to allow a satisfactory determination of whether or not it had any effect.

Often the idea of hiring a cloud seeder does not come up until after a region is suffering from drought. As the period of abnormally low precipitation gets longer and longer, the people involved become more and more desperate and may reach the point where they are prepared to follow almost any course offering any hope of success.

Some of the weather modification schemes offered to the public over the years have been in the class of the patent medicines of bygone days. There are many weather quacks on the loose who are prepared to make outrageous claims and impossible promises. Beware the man who offers to flood the countryside for a trivial price. Beware the one who says it is easy to change dry, blue sky to wet, gray clouds merely by shining special radiation heavenward. There are professional weathermen just as there are professional medical men. If you are interested in weather modification work, get a professional. Ask for credentials and deal only with those who have the meteorological training and background to advise you properly and give you what you pay for.

Before closing this chapter, let us reiterate that it appears that reasonable average increases of precipitation by means of cloud seeding, if they occur at all, might be about 10 to 20 per cent. Recognize that these are increases above that which would have fallen had there been no seeding. This is an important point to note. For example, imagine that you live in an area where normal yearly rainfall is forty inches per year. During a particular drought year, the actual amount might be only twenty inches. If seeding had been employed and was 20 per cent effective, it would have increased the rainfall by 20 per cent of twenty inches. Thus a total of twenty-four inches would have fallen rather than twenty inches. Of course, the extra four inches would have been welcome, but they would not have broken the drought. The year's rainfall would still have been sixteen inches below normal.

There is no evidence to indicate that cloud seeding can either produce or end a drought. When one occurs, it is a reflection of a persistent pattern of airflow inhibiting the formation and frequency of the type of clouds normally expected. Even the most optimistic meteorologist is not prepared to suggest that cloud seeding can influence weather patterns over a prolonged period of time.

In conclusion, over the last decade there have been some important changes in the scientific attitudes about

the efficacy of rainmaking. Not too long ago, a relatively small fraction of meteorologists believed that cloud seeding could increase rainfall substantially. The remainder either were convinced it could not, or were very skeptical. Today the fraction of believers is substantially greater. There are more scientists who are ready to say it is possible to increase rain or snow, but that carefully designed and conducted experiments are needed in order to get convincing answers.

9

CUTTING THE HAIL TO SIZE

Hail occurs infrequently in most parts of the world. When it falls it causes excitement. People run to see it hit and bounce and roll along the pavement. Children rush into the streets and pick up the hailstones and roll them around in the palms of their hands. As long as the ice particles are small in size and number, they do no harm. In some areas, however, as we mentioned in the first chapter, hail ranks high on the list of natural enemies. Hailstorms regularly flatten crops and destroy fruit orchards.

We saw in Chapter 2 that people declared war on hailstorms many centuries ago and that in 1907 an Austrian professor said, ". . . the end of weather shooting has been sealed." Not quite! Not by a long shot, or should we say not by a rocket blast!

Shortly after World War II, some rocket manufacturers in northern Italy began making small rockets for shooting at hailstorms. They were constructed of cardboard and wood, simple to launch and inexpensive—about ten dollars each. (See Plate 17.) The farmers must have been convinced that they were of value, because some 100,000 were fired in 1959 alone. The rockets have been used in other countries in Europe with relatively little enthusiasm. There has always been the bothersome question of how the explosion of a few hundred grams of black powder at a height of 4,000 feet could affect hail. It is loud, but a nearby lightning stroke is louder. The constituents of the smoke are not considered to be significant. Still, the fruit growers continue to fire them.

An Italian scientist, Ottavio Vittori, made a survey of farmers in northern Italy in search of the reasons why they felt the rockets were effective. A common response was that, within one or two minutes after firing, hailstones

falling in the vicinity became "mushy." If these comments are accepted at face value, it has to be concluded that the explosions were influencing the already existing hailstones as they fell towards the ground. Vittori speculated that perhaps the exploding nose cone caused a shock wave capable of producing many tiny cracks in the ice, making it "mushy." This idea has been both criticized and supported by others who have investigated it.

Relatively little was heard about rocket firing during the early sixties. Then in 1966, H. W. Sansom reported work in Kenya. He wrote that Italian rockets were launched at regular intervals from a site close to the center of a number of tea plantations. Over a four-year period, those tea estates near the rocket launcher experienced less hail damage than those further away, but Sansom offered no new ideas about how this might be explained.

In another article, Sansom noted that the thunderstorm with frequent thunder was less likely to produce hail damage than storms with little or no thunder. It was implied that the rockets might simulate the effects of thunder and lead to less destructive hail.

This question of the effects of explosions on hail is puzzling indeed. Most scientists are not prepared to accept the conclusion that the detonation of less than half a pound of explosive can have such profound effects on hailstones. There seems to be little evidence in support of it. Nevertheless, though the use of the hail cannon has been put to rest many times over the centuries, it has returned in its modern counterpart, the rocket.

OVERSEEDING THE STORM

Imagine that you were given the job of reducing the fall of damaging hail. What would you do? The most obvious move would be to try to prevent the growth of the larger hailstones. This, in fact, has been the aim of a number of researchers over the last decade or so. Two approaches have received a great deal of attention.

We mentioned in Chapter 5 that the growth of hail depends on the presence of large quantities of supercooled

water. If it did not exist, hailstones could not develop. Since ice nuclei can convert supercooled droplets to ice, why not put into building thunderstorms enough silver iodide to convert almost every cloud droplet into an ice crystal? This is known as *overseeding* the clouds.

In principle, it can be done, but first it is necessary to estimate how much silver iodide is needed. A cubic centimeter of cloud may contain 100 droplets. If a thunderstorm were three kilometers in diameter and an updraft of five meters per second were present, 2×10^{17} droplets would be moving up the cloud each minute. One might expect a gram of silver iodide to produce 10^{13} nuclei per gram, effective at $-10°$ C. If a scheme were available to distribute the nuclei uniformly, about 400 pounds of silver iodide would be used in a single cloud in ten minutes. Multiply it by ten clouds and consider a storm lasting two hours and the quantity approaches 50,000 pounds. Since the cost of powdered silver iodide is about $50 per pound, it does not appear to be practical at this time to attack hailstorms by means of overseeding. Another approach has received considerably more attention.

MORE STONES, BUT SMALLER ONES

Let us assume that in a cubic meter of air there are four grams of supercooled water. If this water were used to produce one hailstone, it would have a diameter of about 2.0 centimeters (a little smaller than an inch). An ice pellet this large would melt very little in falling to the ground. Quite clearly, a shower of hailstones as big as this one could do extensive damage to plants, windows, airplanes and so forth.

Imagine that as a result of cloud seeding, the number of hailstones grown from the five grams per cubic meter of supercooled water could be increased from one to 100. In this case, the five grams would have to be divided 100 ways and would lead to ice spheres having diameters of about 0.4 cm. On typical hailstorm days, such particles will melt before they reach the ground and instead of hail,

there will be rain. Instead of bombardment by ice, there will be beneficial watering.

Most efforts to suppress the fall of damaging hail have been along the lines suggested by our example. The object of the seeding has not been to inhibit completely the formation of hail, but rather to produce many more stones than would have formed naturally. In theory, such a scheme could lead to stones small enough to melt completely during the fall from the freezing level to the ground. In general, this represents a fall distance of perhaps 10,000 to 15,000 feet.

There have been few systematic experiments designed to study whether or not hail could be influenced by means of cloud seeding, but a number of commercial cloud seeding operators have been engaged in projects aimed at reducing the fall of damaging hail. Typical customers have been farmers with sensitive plants such as lettuce or fruit trees. The scientific literature contains little information on the procedures employed in these projects. It appears that the techniques are similar to those used in rainfall stimulation experiments. Growing convective clouds likely to produce hail are seeded with silver iodide particles by means of ground-based and airborne generators or, in some cases, both types of devices.

Earlier, we dwelled on the subject of rainfall variability and the difficulties it introduces in the evaluation of cloud seeding experiments. The occurrence and intensity of hailstorms are even more variable and more unpredictable. The difficulties of ascertaining whether or not cloud seeding influences hail formation are great indeed.

In the early 1960s, the fruit growers in Pennsylvania employed commercial cloud seeders to reduce the occurrence of damaging hail. By means of ground and airborne silver iodide seeding, they intended to produce many small ice particles and rain in place of hailstones large enough to reach the ground and damage the fruit trees. As fate would have it, Pennsylvania, along with most states in the northeastern part of the United States, suffered an unusually prolonged drought from about 1960 to 1965. The general air mass motion was such as to inhibit the growth of

large thunderstorms. There were abnormally few clouds and, of course, abnormally little hail. And, as you would expect, the scarcity of clouds also produced a deficiency of rain. That is what started the trouble.

Some farmers became convinced that the orchardists were responsible for the rainfall deficits. They claimed that the hail suppressors were actually suppressing the clouds and hence the rain as well. Feelings ran high. Arguments by meteorologists that the drought was not man-made were to no avail. The dispute was carried to the state courts and, as a result, cloud seeding came to an abrupt halt. More will be said about the legal aspects of weather modification activities in a later chapter.

A substantial section of the interested public appears to be badly misinformed about the use of cloud seeding to suppress hail. Too many people seem to believe that when a cloud seeding airplane flies in the vicinity of a potential hail-producing cloud, it will rapidly disappear, as if cloud seeding works like a Buck Rogers ray gun. Pull the trigger of the seeding machine and watch the cloud disintegrate.

The author, when addressing a meeting of ranchers in Arizona some years ago, was told by one member of the audience that she was sure hail clouds could be destroyed. She alleged that when a potential thunderstorm was about to move over her ranch, a cloud seeding airplane flew into it and, "The cloud stopped moving," she said, "and fell apart." She was convinced that the seeding airplane, hired by the local lettuce growers, had stopped that hail producer cold, and her thirsty steers wandering the dry, desolate hills were deprived of cool, sweet rains. Do not believe it! A single airplane seeding with silver iodide cannot push thunderclouds around so easily.

Even if the silver iodide crystals affect the cloud in the manner expected, that is, if they produce many small ice particles, it will not cause a large, rapidly building cloud to dissipate. It does not follow, theoretically, that less damaging hail means less rain. According to some conceptions of how thunderstorms work, cloud seeding

might produce less damaging hail and more rain, but this still has to be demonstrated.

The President's Advisory Committee on Weather Modification, in its 1957 report, indicated that the evidence on hand was inadequate to reach any conclusions about the effectiveness of hail suppression projects. The reports of the National Academy of Sciences published in 1966 contain the remark that "There is a wide range of opinion on whether or not hail can be effectively suppressed or its damage mitigated." This statement is based on the fact that projects in the United States have failed to prove that hail can be modified. Long-term experiments in Switzerland and France also have not succeeded in showing that silver iodide seeding reduced hail damage. In Argentina, detailed studies seem to indicate that sometimes seeding may decrease hail, but at other times it might increase it, depending on the properties of the atmosphere in which the hail-producing thunderstorm develops.

In the Soviet Union, a great deal of talent, effort and expense has been invested in the study of the properties of hailstorms and of means to influence them. A major research program is under the supervision of G. K. Sulakvelidze, with laboratories in Nalchik, in the Republic of Kabardino-Balkaria. On the southern side of the Caucasus Mountains at the Georgian Academy of Sciences, another ambitious project aimed at hail suppression has been in progress.

Sulakvelidze's program started in 1957 with a series of field expeditions to observe the properties of thunderstorms. Radar was used to track the storms, balloons were launched into them, airplanes were flown through them. A laboratory was set up to conduct experiments on both warm and supercooled simulated clouds. The properties of ice particles, large and small, were studied to determine how fast they fall and melt. New cloud seeding techniques were investigated.

By the early sixties Sulakvelidze and his associates (notable among them was N. Sh. Bibilashvili) had formulated a *model* of a hail-producing thunderstorm. They visualized that it had an almost vertical updraft with

maximum strength at a level where the temperature was about −5° C. Just above this altitude they pictured a region where supercooled water could accumulate in large quantities. It was here that most hail growth would be expected to occur.

It was reasoned that if silver iodide nuclei could be introduced into the zone containing a high accumulation of supercooled water, it would be distributed among many hailstone embryos and large numbers of small ice particles would form. The Soviet scientists believed that it was important to deliver the nuclei into the cloud at the −6° C level, where the water content was high. Sulakvelidze decided this could best be done by means of artillery. He established a network of 70-mm cannons directed by radar. They fired shells having gunpowder impregnated with silver iodide. Plate 13 shows a drawing taken from a Soviet article illustrating a hail-modification test. Plate 14 is a photograph of one of the field pieces shooting at a thunderstorm.

Experiments were started in 1961 in a limited way. In 1963, the artillery was used to "protect" a farm of about 125,000 acres. Sulakvelidze claimed amazing success. He estimated that the operation cost about 30,000 rubles, but that the value of the seeding in terms of farm production was about one million rubles. Details on the accounting procedures are not available. The crucial part of the story is that Sulakvelidze in 1966 stated with assurance that his group had suppressed the fall of damaging hail. He apparently has convinced a large number of other Soviet scientists, because by 1968 his techniques were about to be used in various places in the U.S.S.R.

In the Georgian region of the Caucasus, thunderstorms were seeded by means of rockets distributing silver iodide. They were fired in such a fashion as to pass through the cloud at about the −6° C level. In 1964, this work was under the direction of A. I. Kartsivadze. Although not nearly as positive as his Soviet colleagues in Nalchik, he presented data leading to the conclusion that if silver iodide is injected into thunderstorms at the −6° C level, damaging hail might be reduced.

It is reasonable to ask, how do the Soviet experiments differ from what other hail seeders have been doing? The chief difference is that the Soviet scientists are delivering the nuclei into the cloud at a prescribed place (near the $-6°$ C level) during the time when the hail is growing. They argue that the ice nuclei will be more effective this way than if they are distributed under a cloud and allowed to be carried to the supercooled levels by the updrafts.

For various reasons, it is difficult to accept the optimistic conclusions at face value. As in all sciences, some independent verification is needed to assure that the results are reliable and reproducible. Such verification had not yet been made in 1969.

In the United States, efforts in the study of hail and its possible modification are still sadly deficient. Sporadic, piecemeal studies have been made. At periodic intervals over the last twenty years or so, attempts have been made to reduce hail by means of ground-based or airborne silver iodide seeding. Most of these programs have lacked sound scientific direction. In some instances, only a few clouds have been seeded and there were inadequate controls to allow a satisfactory discrimination between natural and artificial effects.

If ice nuclei seeding in the Soviet style, or by any other seeding technique, is to be evaluated, it is necessary to design a systematic, controlled experiment. The properties to be compared between seeded and not-seeded clouds need to be subject to measurement. Present technology is such as to allow productive, meaningful research on hailstorm modification. To date, however, the scientific efforts have fallen far short of the technological potential. What appears to be lacking is the scientific creativity and drive needed to formulate a comprehensive attack on the problem and carry it to completion. Until the necessary scientific talent is brought to bear on this problem, progress in the development of practical techniques of hail suppression in the United States is likely to be disappointing.

10

CONTROLLING LIGHTNING

Some two hundred years ago, Benjamin Franklin showed that lightning was an electrical discharge. Since then, scientists and engineers have learned many things about lightning, but still a great deal of its mystery remains. The mechanisms by which clouds are charged are equally puzzling. This measure of ignorance has slowed down the development of techniques to modify cloud electrification. It has not stopped it, however.

WHAT IS LIGHTNING?

The most convenient description of lightning is that it is a huge spark between regions of negative and positive electric charge. The quantity of charge transported during the flash is not particularly large, but the current is enormous. This apparent paradox is explained by the very short duration of the flash.

If the electricity involved in an average lightning stroke were used slowly, it could keep a single 100-watt lamp burning for about three months. A lightning stroke, however, does not move electric charge slowly. It does it in a brief instant of time—less than one hundred millionths of a second. During that flash, the power expended can be very large—more than ten billion kilowatts in some cases. The momentary surge of electric current, sometimes peaking at over 200,000 amperes, produces temperatures close to 30,000° C. It is no wonder that forests can be ignited, homes charred and even sand fused into glass when lightning strikes.

If you examine the literature on lighting, you will find that writers have classified the discharges according to the appearance of the luminous strokes. You will find such names as *fork lightning* for a stroke in which the main

channel divides to form two or more major channels touching the ground. (See Plate 15.) *Sheet lightning* is the bright illumination of those parts of a thundercloud that surround the path of a lightning flash. Many other names are given to lightning events having different visual appearances. All the types fit into two general categories of flashes: cloud-to-ground and cloud-to-cloud.

Airplanes are sometimes caught in the path of a lightning discharge. The electric charge may pass through the metal parts of the aircraft. In general, the damage to military and commercial airplanes is of minor consequence. Small holes a few millimeters in diameter are commonly burned through the metal skin and protruding radio antennas may be burned off. These results are not negligible, but they do not affect the flight characteristics of the airplane. An indirect effect of the lightning sometimes can be more serious. The tremendously bright flash of lightning may temporarily blind the flight crew. If the aircraft is in a turbulent thunderstorm, it is essential that the pilots see the instruments. In order to minimize the effects of a blinding flash at night, the cockpit lights are turned on and the pilots wear sunglasses.

The effects of cloud-to-ground lightning are extensive. We mentioned some of them in Chapter 1. If we could eliminate lightning to the forests of the United States, the savings in timber and wildlife would be enormous.

CHARGING THE STORM

As a large convective cloud grows, various things happen in and around it. An updraft develops and carries growing water droplets to the upper part of the cloud. The updraft also transports electrically charged particles from near the earth to the upper reaches of the cloud. As the water droplets move to subfreezing regions of the cloud, they become supercooled. Some of them freeze. In so doing, they sometimes splinter to form many tiny ice particles. Some ice particles grow and begin falling with respect to the supercooled droplets. They collide and the ice grains may grow and become small hailstones.

All of these processes cause the separation of electric charge. As they do so, the upper part of the cloud becomes positively charged; the lower part, negatively charged. As charging continues, there is an increase in the electric field strength between the negative and positive centers and between the cloud and the ground. After perhaps ten minutes, the field strength may reach the so-called *breakdown potential*. When this occurs, the air can no longer insulate the charges and a surge of electric charge moves between the centers or from one center to the ground. This surge produces the giant spark we call lightning.

After a lightning stroke, the cloud begins to charge again at a relatively slow rate. We mentioned earlier that a flash might last one hundred millionths of a second. The charging time, in some instances, is about ten minutes, or six million times longer than the discharge time.

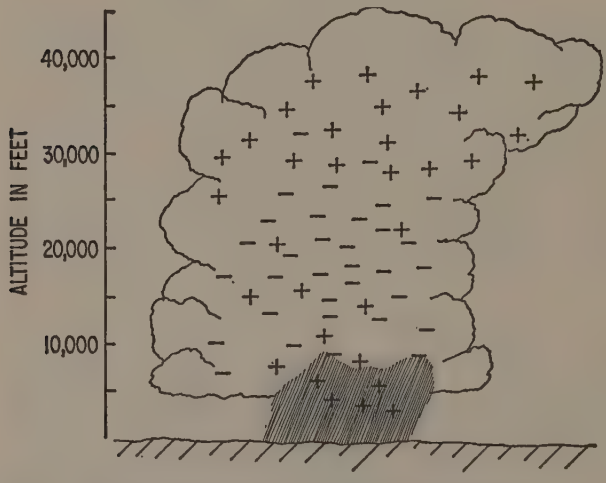


Fig. 8 Electric charges in a raining thunderstorm.

Many observations have shown that, in general, electric charges in a thundercloud are distributed in the manner represented in Figure 8. Negative charges are concentrated in a region just above the 0° C level. The upper

parts of thunderstorms are predominately positive. After a thunderstorm has started raining, a second smaller positive region is sometimes found in the rain area in the vicinity of the cloud base. You should recognize that no two thunderstorms are exactly alike; hence neither are their electrical properties. On the other hand, it is convenient and helpful to construct a model thunderstorm having the features most often observed. All the schemes aimed at modifying lightning have been based in one way or another on those attributes of thunderstorms we have just reviewed. They have been concerned mostly with altering the relatively slow charging process.

Before describing some attempts to modify the electrical properties of thunderstorms, it is important to look at the current views on the charging process. Laboratory tests show that charge is separated when water droplets are broken up, when they freeze, when they melt, when they collide with other water drops or ice particles or when ice particles collide with one another. All these things and more may happen in a cloud. But, you may ask, which one or more of these processes is most responsible for electric charge separation in a thunderstorm?

Although the evidence is not overwhelming, it is the opinion of many authorities that the interaction of supercooled water drops and ice particles of precipitation sizes is most responsible for the charging of thunderstorms. When a supercooled drop collides with a small hailstone, some of the water begins to freeze, while a small fraction may splash off. In the instant of collision and freezing, a negative electric charge is left on the hailstone, while the splashed drops are positively charged. Since they are small and light, they are carried by the updraft to the upper part of the cloud. The heavier, negatively charged hail particles fall to lower elevations in the cloud. If this is the way nature works, it follows that by greatly reducing the quantity of supercooled water, the charging process, and thus the lightning, will be modified.

There are some experts on atmospheric electricity, among whom are Bernard Vonnegut and Charles B. Moore, who are not convinced that electric charge separation and

lightning are caused by precipitation. Instead, they have argued that raindrop formation is augmented by electrical discharges. They maintain that clouds are mainly charged by the capture of *ions,* electrically charged gas molecules and particles. They think of a thunderstorm as a giant Van de Graaff generator with the updrafts and downdrafts acting as belts for the transport of charge. The ions are stored on the cloud droplets. When the stored quantities of charge become large enough, lightning occurs. Vonnegut and Moore visualize that the electrical forces immediately following the lightning flash lead to greatly accelerated coalescence and precipitation growth. They have proposed that cloud charging can be modified by changing the properties of the ions under growing clouds.

MODIFYING THE CHARGING PROCESS

Vonnegut and Moore have performed some fascinating tests that support their views, at least in part. They stretched a wire almost nine miles long and suspended about ten meters above the ground over the countryside of central Illinois. By means of very high voltages, they caused the wire to release ions to the atmosphere. The electric charges attached themselves to air molecules and tiny suspended particles. We can say that the *space charge* was modified.

When small cumulus clouds formed over the vicinity of the wire, air from near the ground was carried up into the clouds. By means of airplanes, measurements were made of the electrical properties of the clouds as the space charge was changed by the electrified wire. The tests indicated that the electrification of the small clouds was being altered in a predictable way. The results indicated that ion capture is an important charging mechanism in small cumulus clouds. Undoubtedly it also affects charge in thunderstorms, but how effective it is in comparison with those mechanisms involving supercooled water drops and ice particles is still unknown.

Most attempts to modify potential thunderstorms have involved seeding with ice nuclei. It has been reasoned

that by reducing the quantity of supercooled water, it might be possible to alter the electrical properties of the cloud. There have been a few tests of the effects of Dry Ice seeding on the electrification of growing cumulus. As the clouds were being seeded, an instrumented airplane measured the electrical field in and around the cloud. Experiments have been conducted both in the United States and the Soviet Union. Although only a small number of clouds were involved, the investigators expressed the view that the seeding caused an increase in the electrical charge of the clouds. It was suggested that the ice particles produced by the Dry Ice caused the separation of electric charge.

Unfortunately, the results just cited are not easily interpreted. Growing cumulus clouds are highly variable and constantly changing. It is difficult to predict what an individual cloud's properties will be ten minutes later. Of course, if the cloud lasts and grows, it can safely be predicted that the bigger it gets, the better the chance that it will be highly electrified. If it grows large enough, it will produce lightning and thunder whether or not it is seeded with ice nuclei.

Again we must ask, how do you determine whether or not an atmospheric event occurred naturally? Once you know enough about a phenomenon, you can predict what will happen naturally and recognize artificially induced effects. Although not all meteorologists agree, it is generally admitted that we still cannot predict the behavior of convective clouds well enough to use solely a forecast to test a weather modification scheme. In order to establish if ice nuclei can influence the electrical properties of thunderstorms, carefully controlled experiments and statistical techniques are needed.

The effects of ice nuclei on lightning have been examined by various groups. During the years 1957 to 1959, the California Division of Forestry carried out silver iodide seeding operations to test if the number of lightning-caused forest fires could be reduced. They concluded that the seeding did not significantly alter the incidence of fires.

At the University of Arizona, convective clouds were seeded with silver iodide during the summers 1958 to 1962 and the frequency of cloud-to-ground lightning was observed. These observations were compared with lightning frequencies on not-seeded days. Days for seeding were selected at random and the lightning observers were not informed on which days seeding took place. After five years of tests, it was not possible to establish any effects of the ice nuclei on the frequency of lightning.

Although these negative results are discouraging, they do not prove that ice nuclei cannot reduce lightning occurrence. The Arizona experiments were not undertaken primarily for the purpose of modifying lightning, but rather to test the possibility of influencing the rainfall process. To initiate rainfall and cause more to reach the ground, the optimum number of effective ice nuclei is perhaps 1,000 to 10,000 (10^3 to 10^4) per cubic meter. It can be argued that in order to greatly reduce the frequency of lightning, the cloud would have to be seeded heavily and the supercooled water virtually eliminated. Certainly in the Arizona experiments the concentrations were far below those needed for overseeding, a fact that may account for the results.

A group of scientists in the U. S. Forest Service station in Missoula, Montana, working under the direction of Donald M. Fuquay, have been engaged in a program aimed at lightning suppression. For a number of years, they have conducted carefully designed experiments in which building thunderstorms have been heavily seeded with silver iodide. Sophisticated equipment has been employed to observe the lightning. In 1968, the research was still actively being pursued. Although the results were somewhat discouraging, the scientists involved were still optimistic that progress was being made and were still conducting field tests.

MODIFYING THE DISCHARGE

Helmut K. Weickmann* and his colleagues at the U. S. Signal Corps proposed that it might be possible to discharge thunderstorms slowly. This would have the effect, if it worked, of eliminating the very rapid discharge associated with the lightning stroke. Weickmann's idea was to disperse a million to a hundred million fine metal strips into the potential thunderstorm. Each of the strips, ten centimeters long, if it did not become coated with ice, would act to discharge slowly a portion of the cloud. It is difficult to draw any conclusions about this scheme until an adequate series of tests has been made in incipient thunderstorms.

In view of the tremendous damage done to our forests every year, there clearly is a need for expanded study of lightning and its suppression. Perhaps the work in progress involving seeding with large doses of ice nuclei will do the job. But in light of past experience and a consideration of how much silver iodide is needed to overseed a thunderstorm, one is led to doubt that this line of attack will offer a practical solution to the problem. In any case, the work now being carried on should help us understand the problem better. Perhaps in this way we will succeed in conceiving new and better methods of modifying lightning storms.

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11

HARNESSING THE HURRICANE

Let us indulge in some fantasy. Put another way, perhaps it would be better to call it wishful thinking.

Imagine the date is August 5, 1980.

Over the South Atlantic, Hurricane Aurora, the first tropical storm of the year, is gathering strength. Wind speeds are over a hundred knots around the eye. Giant waves are reaching more than thirty feet high and throwing angry swaths of foam into the air.

At an altitude of 23,000 miles, at longitude 30° W over the equator, a satellite circles the earth looking down on the Northern Hemisphere. It is a synchronous satellite, so named because its orbit keeps it over the same point as the earth rotates.

The satellite has Hurricane Aurora in sight. The cloud cameras have been recording the storm's development for several days.

Two days ago, Aurora was in the form of broken clouds extending to altitudes of less than 20,000 feet. Yesterday the clouds began to organize themselves. Giant masses of thunderstorms extended into the stratosphere. Today, on August 5, the clouds are arrayed in the form of spiral bands. At the National Hurricane Center in Miami, scientists and forecasters watch the cloud photographs coming from the satellite. The storm is still some five hundred miles from land.

If it were to follow the most common track taken by hurricanes from the South Atlantic, this storm would never get close to land. It would move first towards the west and then swing to the north and then northeast. Following this path, it would do little harm before weakening on its passage over the cooler water of the North Atlantic. But the forecasters do not think this particular storm will follow the usual track. It appears that air cur-

rents will carry the swirling vortex of air so far west that it will strike the Florida coast. This feeling is based not on statistics of past storms or the forecasting experience of the old hands, but on predictions of the pattern of atmospheric motions made by the most refined mathematical equations, produced by some of the keenest minds in the atmospheric sciences.

Just outside of Washington, in a large air-conditioned building is housed the most elaborate electronic computer yet devised. It makes calculations at speeds thought impossible just ten years earlier. The machine's "memory" for information is unbelievably large. Weather observations of pressure, temperature, humidity and wind velocity are funneled into the machine from all over the world, from weather satellites, land stations, sea stations and balloons floating freely at various levels of the atmosphere.

The observing stations are located in all parts of the globe. Some are unmanned, instrumented buoys in the oceans, others are in remote deserts. Communications satellites interrogate the fixed and moving stations and telemeter their records to the master computer—let us call it Alfomega X.

As the millions upon millions of observations are fed into Alfomega X, the machine analyzes them and produces, in a matter of minutes, weather maps of both hemispheres. The results are printed out by super-high-speed printers. At the same time, the operators view the maps on a television screen. In addition, the analyzed maps, each showing the pressure, wind, temperature and moisture patterns, are transmitted via satellite or cable to weather centers all over the world.

In the National Hurricane Center in Florida on August 5, 1980, these maps show that the winds, though a deep layer over the South Atlantic, are moving from east to west. They will carry the storm towards land, which is the cause for concern about the future of Hurricane Aurora. But the storm is still far out over the ocean. What will the atmospheric currents look like tomorrow, the next day and the one after that?

Alfomega X has the answers. The forecasts indicate that

there will be some change in the overall flow pattern of the atmosphere, but not enough. The maps display the future track of the hurricane. It should start to recurve towards the north before hitting the coast, but it will head directly over the city of Jacksonville.

If the hurricane did not threaten to reach land, all that need be done is send out warnings to ships at sea and aircraft, but this storm places a large population center in jeopardy. Some years earlier, elaborate evacuation plans would have been put into effect. A mass exodus would have been initiated. But by 1980, atmospheric scientists have learned how to influence the hurricane.

The meteorologists signal the Weather Control Office to go to work. Within hours, specially instrumented aircraft will swarm into and around the hurricane. We can expect that late in the day, Hurricane Aurora will begin to weaken and become an ordinary tropical storm within twenty-four hours. The East Coast will get heavy rains, but will not be washed by giant ocean waves and destructive winds.

But how did we learn to master the hurricane? The decade of the 1970s had been a memorable one. The moon had been stepped on and picked at. Stones had been brought back to earth and analyzed. Soon the moon lost its mystery and Venus and Mars became the next mountains to climb.

But even before the dawn of the first day of 1970, it became dramatically clear that for a great many generations to come, we would have to squeeze a great many people on Planet Earth. It was necessary to make it a safer and more productive place to live. A tropical storm sweeping up the eastern part of the United States, across the islands of Japan or into the Asian Subcontinent made these places anything but safe. One violent hurricane could cause fantastic destruction, misery and death.

We had conquered the moon. Could we conquer the hurricane? This was one of the mighty challenges of the seventh decade of the twentieth century. With massive federal funding and persuasive encouragement of the President and Congress, the people accepted the chal-

lenge. Scientists from a wide spectrum of disciplines, engineers from all branches of technology, government, industries and universities joined to meet the challenge. The slogan was "Harness the Hurricane by 1980."

Many facts about hurricanes were already known, but even more were guessed at, not understood, or misunderstood. The creative talents of the more than 1,000 scientists and engineers were turned loose on this problem. In time they uncovered the reasons why hurricanes form when and where they do over the warm tropical oceans.

The role of the ocean and the processes by which heat, moisture and momentum are transferred from air to sea and vice versa, became clear. How air motions produce clouds and how clouds in turn affect air motion was finally settled. The factors governing the formation of the "hurricane eye" were elucidated. The mechanisms for the development of the massive clouds surrounding the eye were determined.

New devices were developed and used to map the properties of the clouds, their temperatures, water contents and vertical motions. The role of radiation in transferring heat to and from the storm and the surrounding atmosphere was clarified. These points and many others were tackled successfully in the laboratories and the atmosphere. Theoretical analyses were made and solved by means of computers.

The fall of 1975 was an active one. Four hurricanes hit the eastern and southern United States. Congress was getting impatient; the press, indignant; the public was discouraged; the project administrators were asking for more money; the scientists were working longer hours.

By 1976, clues on the weak links in the hurricane's chain of development were discovered. Experiments on modification began. It appeared that by tampering with the energy transfer mechanisms, the storm's airflow system could be altered. By working one side of the storm, its path might be changed.

In 1978, a group of young scientists, with doctorates just barely dry, found the way to change effectively the energy transfer in the hurricane. Success was barely a

year away. The hurricane was harnessed in 1979. And "We did it first," said headlines from New York to San Francisco.

REALITY

What a supreme pleasure it would be for a meteorologist to be able to say that the daydreams we have just entertained were actually real! Of course we are far from being able to modify hurricanes. At the rate the research programs are moving today, it will take many decades just to learn whether or not they can be modified.

Unfortunately, as already mentioned, many fundamental steps in the lifetime of a hurricane are poorly understood. We know hurricanes form over warm oceans during the autumn of the year. The trigger appears to be a combination of events. When certain types of wind disturbances in the upper and lower atmosphere become superimposed, the warm, humid tropical air rises. This leads to clouds and rain and warming of a large mass of ascending air. A continuation of this process brings about a fall of pressure and a tropical cyclone begins.

If the atmosphere is suitably unstable, the cyclone intensifies. Air rushing towards the center is set in a counterclockwise rotation around the low-pressure center. More of the same, that is, ascent of warm humid air, more heat released and lower pressure, brings about a faster and faster whirl of air. After several days, a violent vortex some 100 miles in diameter may be produced. It is called a hurricane when the winds exceed seventy-five mph, but in extreme cases they can approach 200 mph.

Hurricanes commonly form within the broad sweep of the northeast trade winds. They carry the storms westward in much the same way a river carries along little whirlpools formed at the edge of a protruding rock. Over the eastern part of the North Atlantic and Pacific oceans, the major air circulations begin turning from southwestward to westward to northwestward, to northward. They usually carry the hurricanes with them along a curving path leading to the colder waters over the northern oceans.

Sometimes, however, the patterns of air currents differ from the one we just described. On these occasions, hurricanes follow very erratic paths. They may move westward directly over the Florida peninsula, at times making it to the Mexican coast. Some hurricanes slow their travel for days at a time. Or a track occasionally makes a loop so that the storm passes over the same place twice. As is the case with many properties of the atmosphere, it is convenient to talk about a normal behavior of hurricanes. But it should be remembered that the abnormal event is not a rare occurrence.

SOME PROPERTIES OF HURRICANES

The configuration of clouds and rain in a hurricane is best illustrated by means of satellite and radar photographs. (See Plates 16 and 18.) Plate 16 shows the clouds looking down from above. Spiral cloud bands curving counterclockwise towards the center are dramatically illustrated.

Radar sets of the type used for hurricane tracking do not detect cloud droplets. They "see" only rain, snow and hail. The radarscope photographs again illustrate the spiral nature of the clouds and showers, although they do not always look this way. Sometimes only a circular ring of the raining clouds is detected.

On a radar set, the hurricane "eye" appears as a clear area at the center of the storm. This feature has always been a source of wonder. As the storm approaches, the violent winds and driving rain are terrible to experience. When the edge of the eye arrives, the wind suddenly drops, the sky opens up and the sun shines through broken clouds. Within the eye there is widespread downward movement of air, accounting for the breaks in the clouds. (See Plate 19.)

Since the eye may be on the order of ten miles across, the good weather may continue for perhaps an hour in some cases. It may seem the storm is gone, but that is only about half true. Suddenly the back half of the storm arrives and the hurricane gales and torrential rain return.

Surrounding the eye there are usually huge clouds ex-

tending to great height, forming what are called the *wall clouds*. Airplane flights through these clouds have shown that they are rich in supercooled water. This discovery has led to a series of tests involving the ice nuclei seeding of these clouds, in the hope of causing detectable changes in the hurricane.

SOME SEEDING EXPERIMENTS

The first attempt to modify a hurricane by means of cloud seeding was made by Irving Langmuir and his colleagues on General Electric's Project Cirrus. On October 13, 1947, a hurricane off the southeast coast of the United States was seeded with about two hundred pounds of Dry Ice. Following the seeding, the hurricane pursued an erratic and unexpected course. Instead of passing out to sea, it changed direction and moved inland. Langmuir concluded, after examining the probability of the observed track, that there was considerable evidence that seeding hurricanes does tend to change their behavior.

This conclusion was not accepted by most meteorologists. Some ten years later, another detailed analysis of the case was made by a group of meteorologists in the U. S. Weather Bureau. They inferred that the track followed by the hurricane of October 13, 1947, could be accounted for by a consideration of the general airflow pattern surrounding the storm.

Following the seeding experiment in 1947, Langmuir had observed:

> It seems to me that next year's program should be to study hurricanes away from land, maybe out considerably beyond Bermuda, out in the middle of the Atlantic. . . . I think the chances are excellent that, with increased knowledge, something can be done. The stakes are large and . . . I think we should be able to abolish the evil effects of these hurricanes.*

* "The Story of Cloud Seeding," General Electric *Review*, November 1952.

Many years were to pass, however, before another hurricane was seeded with ice nuclei. First of all, the lack of a suitable physical model made it evident that it would be difficult to distinguish effects caused by the seeding from the natural variations. Secondly, there was a fear of possible lawsuits which might arise if a hurricane heading for the open sea reversed its track and moved over land. In 1958, the National Hurricane Project of the U. S. Weather Bureau seeded a segment of a rain band in a hurricane with a single, silver iodide airborne generator. It was not possible to establish if the seeding had any effect.

It appeared at this stage in the late fifties that in order to bring about marked results, a technique for massive seeding was needed. Coincidentally, at the Naval Ordinance Test Station in California, Pierre St. Amand had developed a number of pyrotechnical devices for ice nuclei production. Several types of flare and solid rocket-fuel mixtures were impregnated with silver iodide. On ignition, the burning mixture vaporized the silver iodide and produced ice nuclei.

St. Amand contacted the author and expressed an interest in using the new devices for seeding large storm systems. He was referred to Robert H. Simpson, director of the National Severe Storms Project. A co-operative agreement was reached and in 1961 Hurricane Esther was seeded.

A U. S. Navy jet airplane flew over the storm along the eye-wall clouds. In its bomb racks was a string of "Alectos," the name given to St. Amand's seeding devices. At the appropriate time, the pilot pushed the release button and the Alectos dropped in sequence. When clear of the airplane, they ignited. Each one fell about 20,000 feet in about forty seconds, trailing a plume of silver iodide nuclei all the way.

Airborne radar sets observed the seeded clouds and detected some changes in the intensity of the radar echoes. In addition, it was reported that the maximum wind speeds decreased by about 10 per cent. The possibility that the changes had occurred by chance could not be ruled out.

Nevertheless, the results were sufficiently encouraging to lead to expanded efforts.

PROJECT STORMFURY

In 1962, Project Stormfury was officially established as a co-operative program of hurricane research and modification. The chief participating agencies have been the U. S. Weather Bureau* and the Navy.

In order to do the job that was felt to be necessary, eight specially equipped airplanes were assembled. Three Navy jets were to be used to seed clouds and take photographs. Two Navy Constellations were equipped with an assortment of radar sets to monitor the clouds and precipitation. Three Weather Bureau airplanes were to penetrate the hurricanes, measuring winds and the properties of clouds.

It was recognized that because of the great variability of hurricanes, it would be difficult to sort out real from artificial effects unless significant changes occurred. If anything was to be learned from seeding infrequent hurricanes, it would be necessary to have some prediction of what might occur normally shortly after the seeding. This in turn required some type of physical model of the storm.

The model which has been used depends on a number of known and speculated properties of hurricanes. Observations reveal that the very strong winds are usually confined within an area perhaps fifty miles in diameter and associated with a nearly circular pattern of *isobars,* or lines of equal pressure. Lowest pressure is observed at the hurricane center and increases outward. The closer the isobars, the stronger the winds. Maximum speeds are in the vicinity of the deep wall clouds. As we already mentioned, some aircraft observations have shown that these clouds contain large quantities of supercooled water.

If the supercooled water could be rapidly converted to ice, the vertical column of air might be warmed by perhaps

* Currently, the Environmental Science Services Administration is the responsible agency. This organization, formed in 1965, encompasses the Weather Bureau.

a degree. The chief scientists of Project Stormfury reasoned, as a working hypothesis, that the warming might lead to a change of the pressure distribution of the storm and cause a reduction in the maximum wind speeds. Robert H. and Joanne Simpson of Project Stormfury speculated further. They theorized that the changes in pressure and wind distribution might convert a hurricane into a more ordinary tropical storm with only moderate winds, but plenty of rain.

In 1963 Project Stormfury seeded Hurricane Beulah. The changes following the seeding were small, but in the expected direction. Whether or not the seeding caused them still is not known. Through the spring of 1967, no other hurricanes were seeded, mostly because none occurred over the area selected as the test site. It was located in the South Atlantic some hundreds of miles northeast of Puerto Rico. Figure 9 shows the seeding area and the tracks followed by two 1965 hurricanes which came close to the area. Particular note should be taken of the behavior of Hurricane Betsy.

On the morning of August 30, 1965, it appeared that Betsy was about to move over the target area and become an ideal test case. Airplanes were deployed to Puerto Rico to prepare for the tests. Before any seeding was done, the hurricane made an abrupt change of course. Instead of heading towards the north and then northeast, as Elena did about a month later, Betsy moved directly westward before starting to recurve. On September 5, it made a complete loop and headed south, then west over the southern tip of Florida. It traveled inland over Louisiana late on September 9.

Bear in mind that this hurricane was not seeded. If it had been seeded, either on August 30 or September 4, many people would have insisted that the sharp changes of direction were caused by the seeding. Hurricane Betsy is estimated to have caused 1.4 billion dollars worth of damage. Had it been seeded on one of the crucial days just mentioned, the courts would, in all likelihood, have been besieged by lawsuits alleging that the seeding caused the effects and hence that the seeders were responsible for the

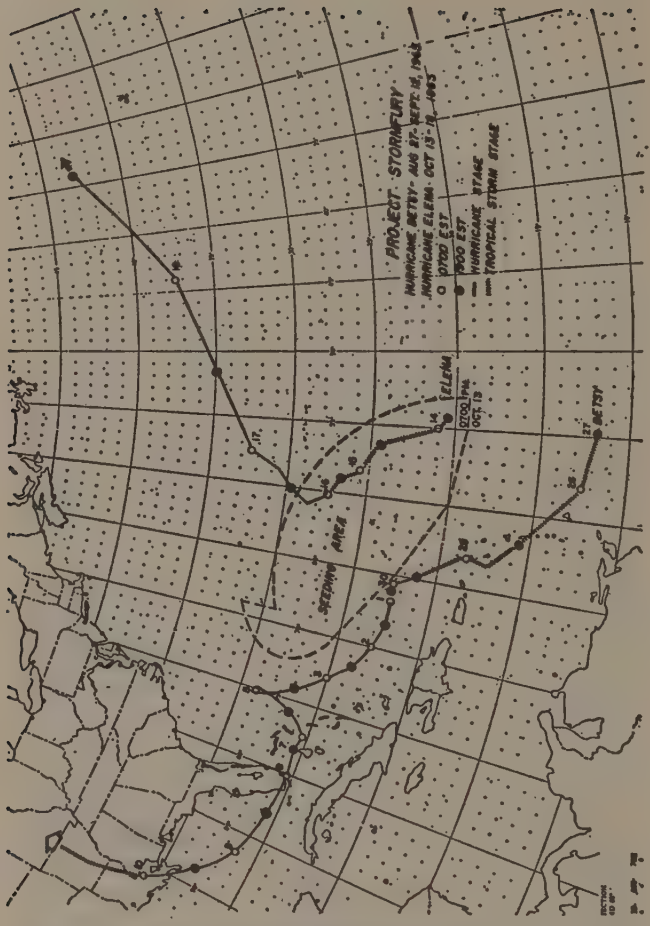

Fig. 9 Tracks of hurricanes Betsy and Elena in 1965. Also shown is the region into which hurricanes had to move during 1965 before they could be seeded. Neither storm was seeded. From a report by R. H. Simpson and J. Simpson.

damage. The thought of such a possibility must send shivers through the scientists of this project, but the research goes on. If hurricane modification is ever to be achieved, it must be possible to conduct research without the risk of financial disasters to the investigators.

The sudden changes in the path of Hurricane Betsy were unusual, but such behavior has happened in the past. It illustrates how difficult it is to evaluate the results of modification experiments.

In the spring of 1967, the scientists of Project Stormfury broadened their area of operation to increase the chances of finding hurricanes for experimentation. Unfortunately, no storms occurred in the area through 1968, and the project entered the next hurricane season hopeful that some suitable storms would present themselves.

Many meteorologists are not convinced that hurricane behavior—their movement or intensity—can be changed by means of ice nuclei seeding. As a matter of fact, some theoretical work in 1967 by Katsuyuki Ooyama at New York University raised serious doubts that cloud seeding will affect the storm system. Seeding could modify some cloud properties without changing the dynamical properties of the hurricane vortex. Ooyama's research shows that storm dynamics depends mostly on the temperature of the ocean water under the hurricane.

CYCLONES IN MIDDLE LATITUDES

Before mentioning some other ideas on modifying hurricanes, a few words might be in order about the testing of a scheme to modify cyclones in middle latitudes. A cyclone is a low-pressure storm system, usually several hundred miles in diameter. Cyclones are the common storms occurring often in the winter over the United States. Almost any weather map will show several of them. Incidentally, a hurricane is a special type of tropical cyclone.

A group of meteorologists at New York University, under the leadership of Jerome Spar, studied the effects of ice nuclei on cyclone development. During nine months

of the winters of 1953 and 1954, thirty-seven cyclonic situations were selected for investigation. Of these, nineteen were seeded by means of silver iodide generators on the ground and Dry Ice dispensers on airplanes. The remaining eighteen storms were used as control storms. Spar concluded: "It is apparent that the seeding in this experiment failed to produce any effects which were large enough to be detected against the background of natural meteorological variance." In other words, no effect could be demonstrated.

But this does not mean that another modification scheme, designed to cause specific changes at a specific point in the life of the cyclone, might not be effective. In order to find the tender places in the cyclone, more extensive theoretical studies of the development and decay of these storms are needed. In the last few years, as computers have made it possible to investigate the factors governing cyclone behavior, cyclones have received increased attention.

OTHER IDEAS ON HURRICANE MODIFICATION

The few exploratory experiments in hurricane modification mentioned earlier involved seeding with ice nuclei. Other ideas have been advanced, but for various reasons have not been tried.

Quite a few years back, it was suggested that the path followed by a hurricane could be influenced by setting oil fires over the ocean surface. It was proposed that many tens of square miles of water be covered with an inflammable fluid and ignited. It was argued that the heat would cause the air to rise and lead to a reduction of pressure, and, in turn, to a change in the path followed by the storm. Because of the large quantity of fuel which would have to be transported and dumped, this scheme does not appear to be practical.

A few years ago, Robert H. Simpson put forward the idea that it might be possible to alter the behavior of hurricanes by modifying the transfer of radiant energy over the storm. He indicated this might be accomplished by means of large numbers of tiny plastic bubbles distributed

by airplane over the top of a hurricane. With the proper type of bubbles, it might be possible to trap the outgoing long-wave radiation in the manner of a greenhouse. If this occurred, it would lead to a warming of the upper part of the hurricane and its environment. It can be speculated that such warming might lead to a reduction of the intensity of the hurricane.

Another avenue of attack on the hurricane is through its lower boundary at the sea surface. Most of the energy for maintaining the hurricane comes from latent heat transported into the storm clouds following evaporation of warm ocean water. If the flow of latent heat from the sea could be reduced, the hurricane intensity should be reduced. This is what happens when one of them passes over land or over cold ocean water. As the flow of energy into the hurricane is diminished, the winds decrease and the storm takes on the characteristics of an ordinary cyclone. Research by Ooyama, mentioned earlier, supports this idea on hurricane behavior.

Two schemes have been proposed to lessen the flow of latent heat. One of them involves the spread of a chemical film over the water to reduce evaporation. Several substances, such as hexadecanol, have been used to suppress evaporation over small reservoirs and ponds. When it is dispersed in powder or liquid form, it produces a film only one or two molecules thick over the surface of the water. Unfortunately, waves break the film and winds blow it away. When you consider the strong winds and giant waves in a hurricane, the use of very thin films spread over regions perhaps 100 miles in diameter, offers very little hope for success.

Recently, Verner E. Suomi at the University of Wisconsin suggested another idea for modifying the lower boundary of the hurricane. The temperature of the ocean water decreases with depth. Suomi proposed that some means be sought to stir up the water through a depth of several hundred feet, thus reducing sea-surface temperature by several degrees. He suggested it might be accomplished by having two submarines or boats drag a long cable suspended between them. This sounds like a formidable task when

you picture the violent state of the sea in a hurricane. Perhaps underwater explosives would be a better way to do the job.

At any rate, this idea and the others mentioned above need more attention. Before making any claims as to possible usefulness, they need to be examined from various points of view. How practical are they in accomplishing the changes in temperature they are aimed at producing? How much will they cost? Most important of all, what effects, if any, will they have on the behavior of a hurricane?

DIFFICULTIES AND ASPIRATIONS

The paucity of knowledge about the details of hurricane inception, growth and movement makes it difficult to do much more than engage in exploratory modification experiments and in speculation about what might have happened. But many meteorologists believe that it ultimately should be possible to influence hurricanes, because they follow natural physical laws. As we learn more about the particular laws governing tropical storms, it is reasonable to expect that ways will be found to influence them. The approach will have to be directed at a "weak link" in the sequence of storm evolution. Remember that a hurricane is powered by heat released during the condensation process in its cloud systems, and in a moderately sized, mature hurricane, the energy released in a single day is equivalent to about 10,000 one-megaton hydrogen bombs. Clearly it is hopeless to try to overpower a hurricane.

We need increased knowledge to find the Achilles heel in the storm. This can come about only if there is a large expansion in research effort. More talent and greater resources are needed so that the problem can be attacked more vigorously in the laboratory, in the atmosphere and via theoretical studies. In view of the fantastic destruction and loss of life caused by hurricanes, who can argue that such an effort is not a necessary one?

12

CHANGING CLIMATES

The climate in any region depends on many factors. We have known for a very long time that the proximity of large bodies of water, oceans in particular, has a profound effect on the climate. The oceans act as huge reservoirs of heat. Their temperatures change more slowly and by a smaller amount than those of the continents. As a consequence, the sea is warmer than the land in winter and cooler in summer. The temperatures of land areas downwind are moderated by winds from over the oceans. These areas are warmed in the winter and cooled in the summer.

The altitude and latitude of a locality also have important effects on its climate. In general, the greater the elevation and the higher the latitude, the cooler the region is likely to be.

A great deal can be said about the climate of a particular place if you know its geographical circumstances, but it is impossible to explain the variation of climate over the earth without considering the motion of the air. As we have mentioned, air movements at any instant determine the weather. When the air rises, clouds and precipitation may be produced; sinking air inhibits their development. In a similar fashion, the climate of a region depends on the prevailing movements of the atmosphere.

THE GENERAL CIRCULATION

If air motions are averaged over a long period of time, we obtain a climatic picture, called the *general circulation.* The character of the general circulation, that is, the strength of wind currents and the behavior of high- and low-pressure systems, depends on many factors. Of primary importance is the temperature difference between equator

and polar regions. The configuration of oceans and continents and the character of the land masses also affect the airflow.

The prominent features of the general circulation have been known for centuries. The northeast trade winds between the equator and about 30° North Latitude blew sailing ships from Europe to the Western Hemisphere. In a belt of latitudes between about 30° and 35° North, the winds are commonly light and dry and the skies are clear. In this region, sailing ships of bygone days sometimes were becalmed and drifted for long periods. These latitudes are called the "horse latitudes." It is believed the name came into being because ships carrying horses were sometimes forced to throw them overboard when water and feed neared exhaustion. At higher latitudes, between about 30° and 60° N., westerly winds predominate. Still further north, east winds again prevail. The Southern Hemisphere has similar patterns of air motions: southeast trades, westerly winds and easterlies near the pole.

The streams of air we just mentioned are related to the patterns of atmospheric pressure. Winds in the Northern Hemisphere blow in such a direction that if the wind hits your back there will be low pressure to your left. Thus air moves counterclockwise around centers of low pressure. On the other hand, the winds move clockwise around centers of high pressure. Some pressure systems are very persistent and exert important controls on the weather and climate.

As we have already noted, the climate in any region is governed by the predominant air motion. When descending air prevails, as it does under the eastern extension of prevailing high-pressure systems, clouds and rain are scarce and deserts are common. Many are found between latitudes of 15° to 30° North and South. Some deserts are in continental interiors; others are found along coastlines, in western South America and southern Africa, for example. Over the years, it has often been suggested that if you build a lake, you will get more rainfall downwind from it. It is visualized that water evaporated from the lake will cause the humidity of the air to increase and

produce more clouds and rain than would occur if there were no lake. The weakness of this suggestion is illustrated by observing the location of deserts. Extensive deserts with less than ten inches of rainfall per year are found along ocean coastlines. So unless the atmospheric motions cause the air to rise, the nearness of bodies of water has little effect on rainfall. In the wet parts of the world, along the equatorial zone, for example, air motions tend to be upwards. In those regions where the air is humid and unstable, thunderstorms and heavy rain are common.

At more poleward latitudes, much of the precipitation is associated with low-pressure systems. The wind flow in these systems causes the air to rise. The ascent of the air is gradual, amounting to speeds of centimeters per second rather than meters per second in thunderstorms. Nevertheless, the ascending motion can last for many days and produce large quantities of rain or snow.

CLIMATES OVER THE AGES

You might think that over the ages there has been little change in the climate. This is far from true. In a variety of ingenious ways, scientists have been able to infer certain aspects of the earth's climate dating back many millions of years. For example, geological evidence of glacier activity has made it possible to discriminate cold, wet periods from warm, dry periods; fossil remains in ancient rocks have been of value in ascertaining old climatic conditions.

Over the last ten thousand years, following the last major ice age, there have been some marked climatic changes. From about 5600 to 2500 B.C., the climate was warm and moist. For the next 2,000 years, there was a gradual decrease of rainfall and temperature, punctuated with spells of very dry weather lasting a couple of centuries.

Starting about 500 B.C., an abrupt transition towards wetter and cooler conditions began. Glaciers advanced into Scandinavia and Ireland until about 200 B.C. By the dawn of the Christian era, the climate had changed significantly. It was about as it is today. Over the last two thousand

years, there have been periods of cold, wet weather such as the Little Ice Age from 1650 to 1850, but for the most part the climatic variations have not been as extreme as in the distant past.

How do scientists explain the changes in climate? What starts an ice age? What caused the retreat of the glaciers? Many theories have been conceived to answer these questions, but none of them is completely satisfying; that is, none of them adequately explains all the known facts. Some appear to account for the slow changes occurring over periods of thousands of years. Explanations for the modifications over periods of fifty to one hundred years should be easier to track down. The difficulty in arriving at a satisfactory theory has led to the conclusion that the crucial factors affecting climatic fluctuations are subtle ones. Small effects at a particular place and time may start a "chain reaction" leading to major effects. In recent years, atmospheric scientists are becoming more concerned with the possibility that human activity may be supplying the "small effects" which might lead to major climate changes.

MAN'S EFFECTS ON CLIMATE

Human activities have been changing local climates for a long time. Of particular interest and potential importance has been the growing quantity of pollutants in the atmosphere. In Chapter 3 we discussed how carbon dioxide gas produced by the burning of fossil fuels might affect world-wide temperatures. Certain aspects of the interrelation of carbon dioxide and temperature still are not clear. For this reason, the effects of increasing carbon dioxide content in the air need further investigation.

The same thing can be said about the concentration of particles that are in the atmosphere as a result of volcanic eruptions, blowing dust and smoke from belching chimneys and motor vehicle exhaust pipes. As we noted in Chapter 3, small particles reflect some incoming solar radiation, but allow rays from the earth to pass out to space. Following the massive explosion of the mighty Krakatoa volcano in 1883, tremendous quantities of dust were thrown into

the atmosphere. They led to a small temperature reduction, perhaps a degree on a world-wide basis.

Only the minutest aerosols may remain in the air for several years. The others are removed by settling out or by being captured by rain and snow. In order for atmospheric particles to lead to long-term cooling, they would have to be steadily replenished in great numbers. The additions of man-made pollutants coupled with contributions from periodic volcanoes might be enough. Could long periods of atmospheric cooling start a chain of events leading to another ice age? Some scientists have speculated that it might be possible.

Still another possible cause of inadvertent weather and climate modification has been recognized over the past few years. It involves the addition of certain substances in the upper atmosphere by high-flying aircraft. The new supersonic transport airplanes (called SSTs) are being designed to fly in the stratosphere at altitudes between 50,000 and 70,000 feet. It has been officially estimated that when they come into full service, some four hundred such airplanes will be in operation. If each one makes four flights daily, the total quantity of water vapor released after combustion will be about 150,000 tons per day, or less than three hundredths of 1 per cent of that normally existing in the stratosphere. According to the latest calculations, even if the flights were concentrated over a small fraction of the earth, the effects of the added water vapor would be small.

It was speculated in 1965 that the SSTs would produce persistent contrails that might form a layer of clouds covering a large area. If this happened, the radiation balance of part of the earth would be changed and so might the weather and climate. In view of the very low humidities of the stratosphere, however, persistent contrails are unlikely.

High-flying rockets or bomb explosions can introduce relatively large quantities of various substances into the upper atmosphere. The possibility exists that they may contaminate and modify the atmosphere at an altitude of between 150,000 and 400,000 feet. Of particular interest

are additions of water vapor, nitric oxide, sodium and lithium. It does not seem likely that enough of the first two substances can be added in the foreseeable future. On the other hand, only a few tens of pounds of lithium added in a single year could double the amount normally present above 200,000 feet. Nuclear explosions in the atmosphere have already injected into the upper atmosphere more lithium than the quantity normally found there. The excessive concentrations have persisted long after the explosions. In order to double the total quantity of atomic sodium at very high levels, about ten tons per year would have to be added. By means of rockets and explosives, such quantities are within man's capability at the present time.

It can be expected that in the near future, the high-level concentrations of lithium and atomic sodium will be appreciably increased. As a result, there will be certain changes in chemical processes taking place at high altitudes. What effect, if any, they will have on low-level weather and climate is unknown. More must be learned about all aspects of this problem.

CAN CLIMATE BE CONTROLLED?

Until recent years, the idea that man might be able purposefully to change the climate over large regions of the earth belonged in the realm of science fiction. It is true that in the more distant past an occasional individual with imagination proposed that it might be done. Few scientists took such suggestions seriously.

If you couldn't influence a small cloud system, wasn't it folly to think of influencing the massive atmosphere? Who had the right to imagine changing the climate when so very little was known about it? Over the last two decades, attitudes have changed. We have learned a great deal about the atmosphere. There still are many mysteries, but certain of its secrets have been uncovered.

Models of the atmosphere are reaching a high level of mathematical sophistication. Electronic computers can calculate the state of the atmosphere. Satellites circling the

globe obtain detailed pictures of the cloud cover and measure radiation from the sun and the earth. In the near future they should also measure temperature and humidity in the atmosphere, perhaps even wind direction and speed.

Scientists are learning more about the general circulation and what controls it and causes it to change. Many important details still are lacking, but we do know that the temperature difference between the equatorial and polar regions is a vital factor. This fact has led to suggestions of how the earth's weather and climate could be modified.

A number of people have offered schemes for warming the Arctic. Such a move would reduce the temperature difference between pole and equator and lead to a change in the general circulation. One of the oldest, and most often repeated, ideas envisages coating the Arctic ice with a layer of carbon dust to allow more solar energy to be absorbed. This is expected to increase temperatures and cause melting of the ice.

Professor M. I. Budyko, a prominent Russian scientist, has suggested that once the ice was melted, it would not reform. He imagines that exposed rocks, soil and water would continue absorbing relatively large quantities of solar rays and prevent snow and ice from accumulating in thick sheets. This appears to be an oversimplification. Warming should lead to more clouds, which will reflect the incoming sunlight.

In considering any scheme for modifying the atmosphere, it is necessary to examine the quantities of energy and matter involved. Certainly a coating of carbon black would absorb more heat than white, reflective snow and ice. But how much dust would it take to coat the Arctic? It has been estimated that in order to produce a layer 0.004 inch thick over the area north of latitude 65° North, some *one and a half billion tons* would be needed. This utterly fantastic sum would give only a single coating and more than one would be needed. Clearly the carbon black idea is a hopeless one.

In 1959, a Soviet engineer, P. M. Borisov, suggested that a giant dam be built across the nearly sixty-mile-

wide Bering Strait. He proposed pumping cold water from the Arctic Ocean into the Pacific Ocean. Warmer water from the Atlantic then would flow into the Arctic and might lead to a small, but probably significant, temperature increase.

Another idea offered by M. I. Budyko advocated that the icecap be coated with an extremely thin layer of a chemical substance to reduce evaporation. As was mentioned earlier, films about one molecule thick have been employed to reduce evaporation from small bodies of water. Budyko suggested that by suppressing evaporation, it might be possible to raise the temperature by more than 5° C. In evaluating this scheme, you are again faced with the task of coating and maintaining enormous surfaces.

In 1958, the late Harry Wexler of the U. S. Weather Bureau proposed another technique for warming the Arctic. (Incidentally, he was the first to demolish effectively the carbon black idea by calculating the quantities involved.) Wexler suggested that "clean" nuclear bombs be exploded in the Arctic Ocean in order to propel heat and moisture high into the atmosphere over the polar regions. He argued that this procedure would cause clouds of ice crystals to form. They would act as a shield preventing the escape of the earth's radiation and the trapped heat rays would be expected to warm the lower atmosphere.

All of the schemes we have mentioned and still others involve a great deal of speculation. We are not sure if any of them can successfully warm the Arctic atmosphere. But sooner or later someone probably will conceive an approach which will do so. What then? That is a most vital question.

At the present time, most meteorologists would agree that warming the Arctic by a small amount would change the global weather and climate. Unfortunately, nobody knows *how* it will change. Will the deserts be brought into bloom and the swamps dried up? Or will the swamps be even more inundated and deserts enlarged? Will the farming regions of the world get more or less rain and snow and when will it fall? Will the ocean surface rise and flood the low-lying cities of the world? Will the changes in gen-

eral circulation initiate another ice age? No one yet knows the answers to these and a great many other related questions. Until we do, or at least can take a good guess, we better be careful tinkering with the global atmosphere.

In order to hasten the day when it can be done, we have to learn a great deal more about weather and climate. We need to know more about the inventories of heat and energy in the Arctic. Better information must be accumulated on the relationship of Arctic temperature and atmospheric circulation.

Another path to the eventual goal of changing large-scale weather and climate is the further refinement of mathematical models of the atmosphere so that they conform more closely to the physical realities of the earth's atmosphere. When an adequate model is available, simulation experiments can be performed. For example, the investigator could introduce a hypothetical warming of 1° C in the Arctic. The computer would grind through the mathematical solutions and the predicted pattern of air motions could then be studied. Temperature and precipitation distributions could be inferred and the resulting beneficial or harmful effects in regions of the earth could be ascertained. Other hypothetical changes could be examined by means of the computer. Those showing no promise could be discarded, those offering hope for general improvement could be implemented in the real atmosphere.

Another requisite, before accurate mathematical simulation of the general circulation becomes a reality, is improved knowledge of those factors governing the circulation. Our understanding of the interaction of atmosphere and ocean is far from adequate. Also, the role of the tropics in the circulation picture is still unclear. A great deal more has to be learned about the transfer of radiation in the atmosphere.

Before we reach the stage of satisfactory mathematical testing, better observations of the global atmosphere are essential. This goal is within sight. The government weather services of the world, working through the World Meteorological Organization, have launched a program called the World Weather Watch. By the middle seventies,

the global systems of observation and communication should be much better than they are today.

An international committee of scientific organizations has established a Global Atmospheric Research Program. Its purpose is to develop a better understanding of the atmosphere below about 100,000 feet. It will play a key role in advancing mathematical treatments of the atmosphere. The scientists involved look to the world weather programs as a step towards longer-range forecasts. They also see them as means for learning the keys to the general circulation. Hopefully, one of them will unlock the secret to controlling large-scale weather and climate.

A UNIVERSAL ATMOSPHERE

Before the subject of climate modification is dropped, it is essential that a few words be said about the international character of the problem. When the earth's atmosphere is examined from a high-flying satellite, cloud systems can be seen to form and move in the form of giant swirls some thousands of miles in diameter. They sweep across oceans and land, raining or snowing on many nations along the way. A narrow belt of strong winds in the upper atmosphere called the *jet stream* is closely related to the formation and behavior of storm centers. When drawing weather maps of the Northern Hemisphere, the jet stream can be followed around the globe, crossing continents and oceans.

Changes in the weather over North America do not happen in isolation. They are accompanied by changes around the hemisphere. The atmosphere is one huge reservoir of air. In fact, it is more like a thin shell of air, because some 99.9 per cent of it is within thirty miles of the earth. Motions in one region are accompanied by opposite motions elsewhere. For example, if in one part of the globe the north winds in the winter are abnormally persistent and cold, in another part of the globe, south winds will be abnormally persistent and warm.

The essential unity of the atmosphere means that it is not possible to produce climatic changes over one part

of the earth without causing changes elsewhere. The atmosphere is universal. It belongs to no one. At the same time, it belongs to everyone. We all depend on it to bring clean air on a smoggy day, warm air in the summer and rain to feed the fields. Climate modification, if ill conceived and conducted, without consideration of all mankind, could lead to catastrophe. The collaboration of all nations is needed so that such an event will never come to pass.

PLANTS, ANIMALS, PEOPLE, THE LAW AND THE WEATHER

Most people would agree that it would be desirable to be able to control the weather. But stop for a minute and think of the problems which will arise when the day of weather control arrives.

When New York City needs more water, should the clouds over its upstate watersheds be seeded to try to make more rain? If you think so, you agree with most New Yorkers, but what about the resort owners who want sunny, dry weather? If you could influence the movement of a hurricane headed for the Atlantic seaboard, would you steer it far out to sea? Surely the insurance companies and a great many millions of people would think you should. But what would you do to alleviate the water shortage created by the loss of the rain which would have fallen from the storm?

These are just two of a great many possible questions which will become very important as we learn to modify the weather effectively. Only in the last few years has even a little thought been given to the ecological, social and legal problems of weather modification. A great deal more needs to be learned.

SOME VIEWS BY BIOLOGISTS

In 1964, the National Science Foundation asked the Ecological Society of America to consider the biological effects of weather modification. The society appointed a committee to do the job. It came up with a number of conclusions. Among them were the following:

1. Living things are adapted to the weather that actually prevails, and any change in that weather will be generally deleterious to them.

2. The largest credit item for weather modification is likely to be an increase in primary production of the drier parts of the land surface through improvements in rainfall. Even the ability to control seasonal distribution of rainfall would lead to more efficient farming operations. Realization of the potential increase in production would depend upon being able to modify the rainfall without major pest outbreaks and extinction and disruption of natural communities. It is not certain that this would be possible.

3. The largest weather modification debit item is likely to spring from the decreased stability of communities, which would manifest itself in an increase in pests, weeds, and pathogens. The identity of the species involved in these disruptions cannot be predicted, nor can their cost.

4. For the present, weather and climate modification should be restricted to local small-scale operations.

5. Larger scale operations, such as an attempt to increase the rainfall of any substantial part of this country, should not be undertaken, from a biological point of view, in the present state of knowledge.

6. All weather modification experiments of a scale large enough to have important biological consequences such as those currently envisioned for the Upper Colorado Basin, should be preceded and accompanied by careful ecological monitoring and computer simulation studies. Manipulating the weather to obtain a net benefit will demand much better understanding of the interactions of weather, climate and organisms than now available.

7. Adequate understanding of the interrelationship of weather, climate and ecology will demand a very expensive long-term research program. Present resources of ecologically-trained investigators are inadequate to cope with these problems.*

Clearly the group of ecologists preparing the report showed little enthusiasm for an immediate expansion of rainmaking activities. The suggestion that weather modification programs be suspended until the biological effects

* Report NSF 66-3, *Weather and Climate Modification* (Washington, D.C.: National Science Foundation, 1966).

are better understood is not likely to get much support. Certainly it would be advantageous to know more adequately the interrelationships of weather, climate and living organisms. But the need for greater amounts of fresh water is likely to overwhelm the need for better understanding.

The mood of atmospheric scientists, hydrologists and political leaders is moving increasingly in the direction of a desire to develop reliable means to produce more rain and snow. These efforts will not be delayed until the ecological questions are resolved. Unquestionably, studies of the biological effects of weather modification must be accelerated. Since they probably will not precede efforts to change the weather, they should at least try to keep in step. In some instances, it should be possible to use weather modification projects as ecological experiments.

There also is great concern among wildlife people about how changes in the weather might affect birds and animals in wilderness areas. Again you might speculate on the consequences. And again it is essential that research programs on wildlife be run simultaneously with those on weather modification.

At this stage, the fears of biologists and zoologists appear to be unwarranted, since they are partly based on the assumption that we can make large, sudden and permanent changes in the weather and climate. In other words, they are considering the dangers to the ecological system assuming we could change the climate of areas the size of the upper Colorado Basin. Perhaps this will be possible some day, but it is not right now in the view of most atmospheric scientists.

LEGALITIES

Not too many years ago, rain was regarded as a gift of God. If it rained on your farm but not on your neighbor's, you commiserated with him. There was no dispute over who owned the rain. If it landed on your land, it was yours; if it fell on his land, it was his. The advent of cloud seeding is making people regard rain, snow, hail and

lightning in a different light. They are beginning to develop proprietary attitudes about moisture in the atmosphere. When a cloud drifts overhead, they are beginning to wonder who owns the water in it.

The lawyers have entered the scene, a sure sign that disputes will become more numerous. Unfortunately, there are still many uncertainties about exactly how effective cloud seeding will be in any specific situation. We know some clouds can be modified, we think that sometimes more rain or snow can be produced and we hope to do more about hail, lightning, thunderstorms, hurricanes and tornadoes. But because of the shortage of facts and the paucity of past experience, it is difficult to establish a body of law.

Nevertheless, this has not prevented people from fighting over the weather and suing one another. The first case involving cloud seeding was filed in 1950. A resort owner located in a watershed area sued to prevent New York City from using the services of a cloud seeder to try to increase rainfall during a drought period. The court ruled that the welfare of ten million inhabitants should take precedence over the inconvenience of the resort owner.

In 1959, some Texas farmers conducted a cloud seeding project for the purpose of suppressing the fall of damaging hail. A group of ranchers, who wanted precipitation in any form, were convinced that the seeding operation was reducing the total precipitation. They went to court to stop the seeding activities. As usual, witnesses testified for both sides. The court ruled that the seeding might have been reducing precipitation. An injunction was issued banning further cloud seeding until it could be shown that it would not decrease precipitation. This action closed the door on weather modification experiments in Texas for many years. In 1967, the Texas legislature enacted a state law prescribing conditions under which such experiments could be carried out.

There have been at least seven lawsuits involving cloud seeding in various parts of the United States. Four cases have gone in favor of the seeder and his clients. The Texas suit, as noted above, was decided against the cloud seeder.

In February 1968, Judge John A. MacPhail in Fulton County, Pennsylvania, handed down two important legal decisions. He upheld an Ayr Township ordinance prohibiting the operation of a cloud seeding device and he also upheld a $100 fine levied by a justice of the peace against David L. Fulk for violating the ordinance. At the same session, Judge MacPhail ruled that a township ordinance prohibiting weather modification activities was valid. Furthermore, he held that, "Every owner of land has a property right in the moisture in the clouds and the right to receive that moisture in its natural form subject to such weather modification activities as shall be carried out by governmental authorities in the public, as opposed to private, interest." Between the time that the suits were filed in Pennsylvania and Judge MacPhail's judgments, the state adopted a law for the purpose of controlling weather modification activities in Pennsylvania.

Another kind of dispute involves flooding. In California, following a disastrous flood which caused damage of about $65 million, a group of property owners argued in court that the long-term effects of nearby cloud seeding set the stage for a damaging flood. They sued the cloud seeder (North American Weather Consultants), his client (the Pacific Power and Electric Company) and the State of California for recompense for damages. The court ruled that any increase in rain that might have been produced by the seeding was successfully impounded in a storage lake and could not have produced the flood.

At this time, there is disagreement, even among the so-called experts, about what cloud seeding can and cannot do. As a result, the outcome of lawsuits on weather modification rests largely on the ability of the attorneys involved and the wisdom of the judge. It appears reasonable to expect that as weather modification activities increase, the number of lawsuits will do likewise.

Among scientists doing weather modification research, there is a certain amount of apprehension about the legal aspects of their work. There is a feeling that, sooner or later, a court will find a cloud seeder financially responsible for an undesirable weather change—too much or too

little rain or snow or hail or wind. If such an event occurs, particularly if a large sum of money is awarded, weather modification research in the United States is likely to be seriously retarded. Until recent years it was not even possible to buy liability insurance for such activities, because of uncertainties in establishing premiums, but now insurance can be obtained. Whether this will continue to be so following a very costly lawsuit remains to be seen.

LAWS

By 1969, at least twenty-three states had enacted laws regarding weather modification. They vary widely. Some merely call for registration, others require licensing. Several states wisely demand that prospective weather modifiers give evidence of meteorological or engineering competence. Some states have already claimed that they own the moisture in the air over the state.

It is reasonable to expect that, in the near future, more states will enact ordinances dealing with weather modification. Laws should be based on facts, but in this case, facts are few. On the other hand, speculation is plentiful. One of the dangers is that legislation will be adopted that makes it difficult or impossible to establish the facts. For example, the Pennsylvania state law adopted in 1967 states that, "Any person knowingly having in his possession without registering the same with the department any cloud seeding equipment shall, on conviction thereof, be sentenced to pay a fine of ten thousand dollars ($10,000)." Such a provision and others of a more restrictive nature are serving to discourage research on weather modification. Incidentally, since a carbon dioxide fire extinguisher can be used for cloud seeding, there probably are many Pennsylvanians in violation of the state law.

Surely some legislation is needed, if for no other reason than to protect the people from weather quacks. At regular intervals, so-called weather modifiers appear on the scene with no training in meteorology, almost no

knowledge of the atmosphere, but with great promises and fast tongues.

Certain aspects of the legal problems in weather modification have been analyzed by Howard J. Taubenfeld of the School of Law at Southern Methodist University. His findings have been published in a report of the National Science Foundation. Some of the pertinent points are the following:

> . . . At the present time, the need for controlled experimentation, both by governmental and private research agencies and by commercial operators is apparent if the promise of weather modification is ever to be achieved. At the same time, the public needs not only to be educated but to be protected as well. Community and private interests must, as always, be balanced.
>
> Since weather is "transient" and cannot be bounded by political borders and since experimentation over broad areas is or may become necessary, the utility of uniform legal rules with respect to licenses, operations, liability, ownership, use and control of the elements, and the like seems beyond question. Reporting, both before the activity in order to prevent interference and contamination, and afterwards to permit the collection and evaluation of scientific data, is crucial to progress. Uniform protection of the general public and of those with special concern in the weather against inexperienced and/or irresponsible persons engaged in weather activities and a sharing by all the public in the risks involved in careful, needed experimentation in this new field are also essential. . . .*

The report suggests that although uniform state action is possible, the federal government may have a duty to take on the responsibility of writing appropriate legislation. Of particular importance are provisions for a system of advanced reporting of weather modification activities. Without such information, it is difficult to design

* H. J. Taubenfeld, *Weather Modification: Law, Controls, Operations,* Report NSF 66-7 (Washington, D.C.: National Science Foundation, 1966).

effective seeding operations. Before engaging in a seeding project, it is necessary to know if someone else is seeding just upwind and if ice nuclei are moving over your area. This is because, after a weather modification program is conducted, an evaluation must be made to establish any effects that may have occurred. If nearby seeding is going on, uncertainties about interference could prohibit a reliable evaluation.

Legislation should be such as to encourage research and progress. Provisions need to be made protecting scientists and engineers from crippling lawsuits. Senate bill S2875, introduced during the 89th Congress but never passed, contained such protection. The intent of the bill was to authorize a much enlarged research program aimed at ". . . increasing the yield of water from atmospheric sources."

Section 201 of the bill read as follows:

> Sec. 201. The United States will compensate for the taking of property or rights, or for damage, injury, or for other just claims arising out of execution of the comprehensive program in the manner provided in the Act of August 30, 1954, an Act to amend the Atomic Energy Act of 1946.

A condition such as this would encourage the search for better methods of changing the weather beneficially, while providing compensation for just claims for damages.

At the present time, experts in several law colleges are studying the legalities of weather modification. These authorities should supply leadership in the drafting of state and national legislation which will encourage research and application of weather modification, while at the same time protecting all legitimate interests.

FEDERAL AGENCIES AND WEATHER MODIFICATION

Starting in 1958 the National Science Foundation (NSF) had a specific congressional directive to conduct

programs in weather modification. But in September, 1968, House of Representative Resolution 5404 stripped away this statutory responsibility. This resolution also eliminated the mandatory reporting to NSF of weather modification activities. When the resolution was adopted, it was expected by its chief sponsor, Rep. Emilio Q. Daddario, that other legislation would be passed assigning principal responsibility for weather modification research to another government agency. Unfortunately this did not occur in 1968, and hence, there ceased to be any legal requirements to report the location and time of weather modification projects. In order to evaluate the effects of a cloud seeding project, it is essential to know if there are other nearby seeding activities.

Various federal agencies such as the Environmental Science Services Administration, the Forest Service, the U. S. Air Force, Army and Navy have developed modest weather modification programs. In 1962, through an appropriation of $100,000, the Bureau of Reclamation of the Department of the Interior entered the weather modification picture. That department has been vitally interested in increasing the precipitation over the watersheds. With the assistance and encouragement of the Committee on Interior and Insular Affairs, chaired by Senator Clinton P. Anderson, the Department of Interior program has grown at a lively pace to a level of about five million dollars in 1968, making its weather modification program substantially larger than that of any other government agency. Part of the reason for this relatively rapid growth can be ascribed to the fact that the Bureau of Reclamation, which is running the program, has more or less promised to produce substantial quantities of additional water by the middle seventies. The first annual report, released in early 1968, said, "By 1975, programs within the Colorado River Basin could provide up to 2 million acre feet of additional streamflow at operational production costs of $1 to $1.50 per acre foot," if the research is adequately funded.

Total federal expenditures in the United States for weather modification research were less than three mil-

lion dollars in 1963. In subsequent years, government support increased fairly rapidly to about twelve million dollars in 1968. Although detailed plans for expanded research were prepared by all the interested government agencies, economy moves by the federal government dictated against them. In fiscal year 1969, research in weather modification was funded at about the same level as the year before. All too often, when the government feels it is necessary to economize, science is the first to feel the ax.

The 1966 report of the Academy of Sciences Panel on Weather and Climate Modification cited earlier, took note of the fragmented nature of the research efforts in this subject. It was suggested that the primary responsibility for weather modification should be assigned to a single government agency. Members of the panel visualized that such an agency, if adequately supported, could marshal the scientific talent and equipment to make rapid progress on learning more about the science and application of weather modification.

Various proposals for the centralization of responsibility in this area were submitted to the 90th Congress, but it adjourned in October 1968 without taking any action. It is anticipated, however, that the importance of the problem will lead to congressional action in the not too distant future.

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POSTSCRIPT

We should be able to exert greater control over the atmosphere than we do today. It follows natural laws, as does every other physical system. As our knowledge of the atmosphere increases, so will our ability to manipulate it.

We know we can change certain kinds of clouds. In some cases the quantity of rain or snow can be altered. We appear to be on the verge of learning how to reduce the damaging effects of hail and, possibly, of lightning. Techniques for the modification of tornadoes, hurricanes and other large-scale weather systems may be further down the road. Perhaps man never will succeed in fully controlling the weather, but this is a hopeless point of view. No one can say for sure that we can't learn to improve weather and climate. Doesn't it make sense, then, to move ambitiously forward on the assumption that it can be done? It does to me.

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